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Condensed and Expanded Sections in the Lower Mesaverde Clastic Wedge, Campanian of Wyoming: Evidence for Tectonic Rectification of Sea Level

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**CONDENSED AND EXPANDED SECTIONS IN THE LOWER MESAVERDE
CLASTIC WEDGE, CAMPANIAN OF WYOMING: EVIDENCE FOR
TECTONIC RECTIFICATION OF SEA LEVEL**

by

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B.S. December 2004, Old Dominion University

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ABSTRACT

CONDENSED AND EXPANDED SECTIONS IN THE LOWER MESAVERDE CLASTIC WEDGE, CAMPANIAN OF WYOMING: EVIDENCE FOR TECTONIC RECTIFICATION OF SEA LEVEL

Matthew W. Botzler
Old Dominion University, 2007
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The stratigraphy of the Cretaceous Western Interior basin indicates that sea level oscillated during the late Cretaceous. The oscillations were polyharmonic, with periods ranging from millions of years to hundred thousands and ten thousands of years. However, there is disagreement over the extent to which sea level change was global in nature and the extent to which it was driven by local uplift or subsidence (tectonism). In orogenic regions where subsidence, sediment supply, and eustatic variation are all affecting sea level, comparisons of high and low frequency cycles can help to sort out forcing mechanisms. Low frequency eustatic sea level rise can be amplified by regional subsidence so that high frequency sea level falls are suppressed, and the high frequency oscillations appear as modulations of a steady rise. In such cases, the high frequency signal can be said to have been “rectified”. This thesis focuses on two members of the Eagle Formation in the Bighorn basin of Wyoming, USA, the Virgelle and the Gebo, whose contrasting architectures appear to reflect oscillatory sea level fall (the Virgelle) versus pulsed sea level rise (the Gebo). I hypothesize that Gebo deposition was characterized by intensified sediment input during a variable-rate rise of sea level (pulsed rise) that was rectified by tectonics, resulting in the loss of the 3rd and 4th order sea level falls; whereas in the Virgelle, tectonic rectification was absent during a high frequency

oscillatory sea level fall.

This hypothesis has been tested by comparing several architectural characteristics of the two members; unit thickness, the presence of sequences verses parasequences, the presence of sharp-based shorefaces and gutter casts, the inferred paleo-gradient, sequence of stacking patterns, and the presence of incised valleys and unconformities. The evidence shows that the evolution of these members was coupled closely to eustatic and tectonic changes. At the time of Virgelle deposition, the subsidence rate was too low to reverse eustatic sea level fall, and tectonic rectification did not occur. During Gebo deposition, the changing geodynamics expanded the zone of rapid subsidence and at the same time generated uplifts that shed sediment during a variable-rate rise of sea level (pulsed rise). This then resulted in the loss of the high order sea level falls. The Bighorn Basin appears to be characteristic of the proximal portion of Posamentier and Allen's zone B, where eustatic fall only periodically exceeds subsidence.

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STATEMENT OF PROBLEM

Introduction

Historically, isostasy was considered the main process that forms marine cyclic deposits in developing basins. As Chamberlain (1909) famously said, “diastrophism is the basis of correlation.” In this model, tectonism and sediment supply variations modulate the stratigraphic record. More recently, Peter Vail has argued that diastrophism is not the key to stratigraphic correlation; rather, eustasy is (Vail et al. 1977). Plate rifting, changes in spreading rates, and Milankovitch cycles control the volume of water being forced on land by either displacement, storage on land, or water addition through ice melt. The rise and fall of sea level can be seen in the stratigraphic record. The resulting deposits are of hierarchical scale, ranging from, first, second, or third order sequences to higher frequency fourth and fifth order sequences (Miall 2000; Table 1, this paper). Global sea level change has been well documented, but the relative contributions of eustasy and diastrophism, and synchronicity of the resultant record from basin to basin has been hotly contested (Vail et al. 1977; Miller et al. 1965; Miall 2000).

Tectonic Rectification

The problem of discriminating between eustasy and tectonism as drivers of sea level attains its greatest difficulty in orogenic regions, where the combination of subsidence, sediment supply, and sea level change can create a complex stratigraphic signature. Rises and falls of sea level are controlled by global eustatic changes across a

Table 1.— List of successive orders of sequences and their subsequent durations. (Vail et al. 1977)

Sequence Orders	Duration in Years
1 st	200-300 million
2 nd	10-80 million
3 rd	1-10 million
4 th	100k-1 million
5 th	20k-99k

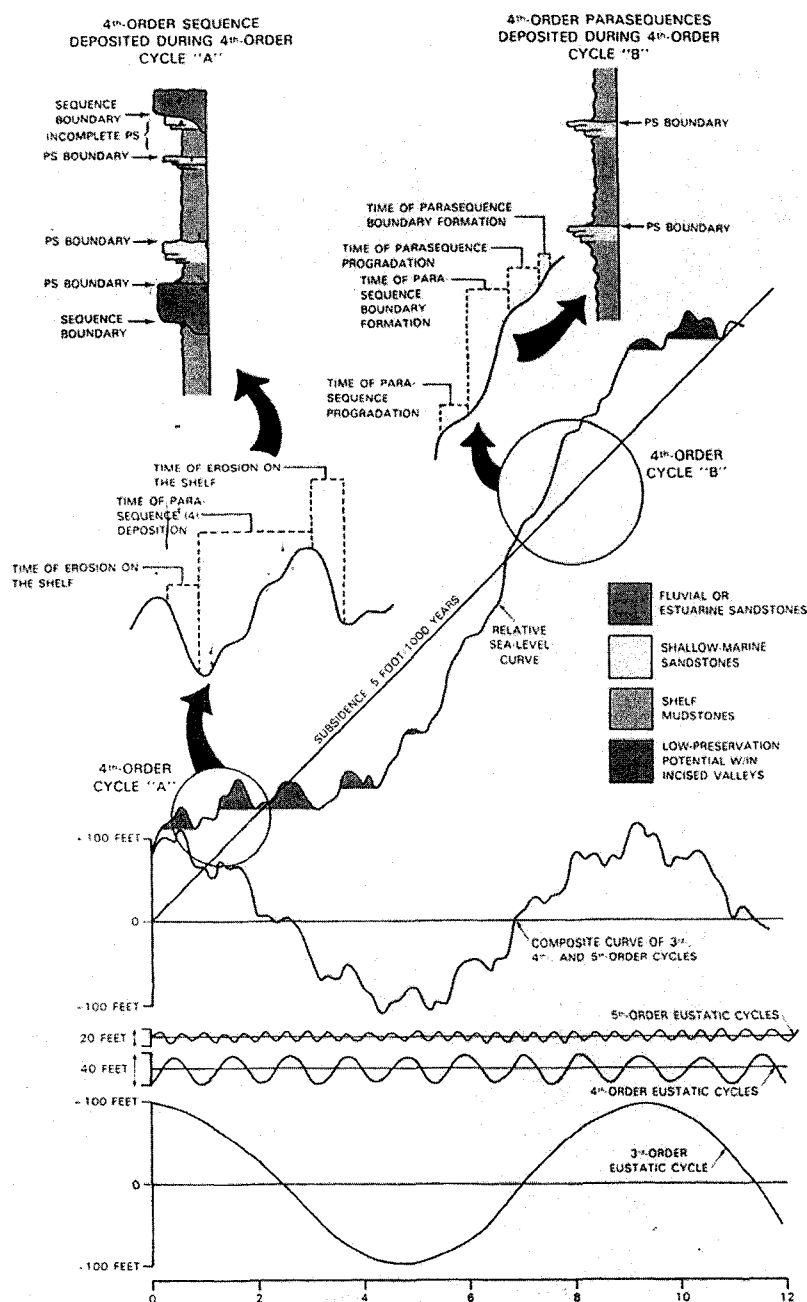


Figure 1.— Composite curve consisting of; 3rd, 4th, and 5th order eustatic cycles plus steady subsidence. The curve shows fifth order parasequences and fourth order tongues, some of which are parasequences and some of which are high frequency sequences, depending on their position on the third order curve. The eustatic sea level curve experiences several oscillations; however, when subsidence is added, fifth order sea level falls are rectified, and appear as reduced rates of rise. (from Van Wagoner et al. 1990)

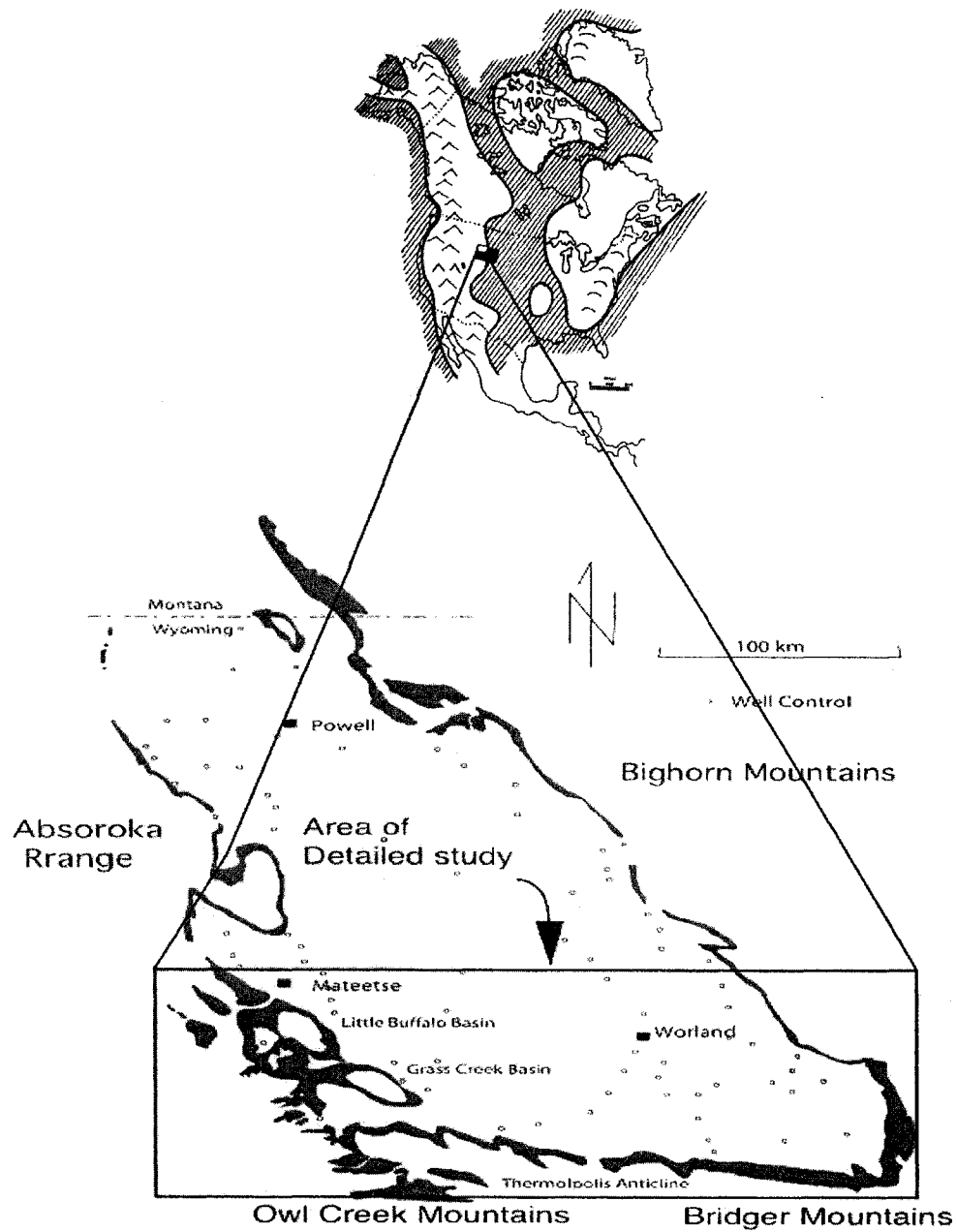


Figure 2.— Diagram of location of study site. Bordered by the Owl Creek and Bridger Mountains, the study site preserved the paleo-shoreline of the Western Interior Seaway. (from Johnson 2005)

range of frequencies (i.e. Milankovitch cycles at high frequencies, or increased sea floor spreading at lower frequencies); however, high frequency cycles can be suppressed or amplified due to local dynamics as they interact with the low frequency cycles. In particular, high frequency drops in sea level on the rising limb of the low frequency cycles can be reversed, so that the low frequency rise is no longer oscillatory but pulsing. Fast rises merely alternate with slow rises (Van Wagoner et al. 1990, see Fig. 1), hence the metaphor of “rectification”, as in the rectification of AC current to DC current. With these principles in mind, tectonic rectification can be a useful tool in testing the relative roles of eustasy and local sea level change.

STUDY AREA

The study area lies within the northwest quarter of the state of Wyoming, U.S.A (Fig. 2). During the late Mesozoic Era, the North American and the Farallon plates converged. The subduction formed the Cordilleran orogenic belt (Armstrong and Oriel 1965; Dickinson and Snyder 1978). During the orogeny, subduction, volcanic arcs, accreted terrains, and fold thrust belts developed (DeCelles 2004). The area underwent several episodes of intense mountain building and thrusting, which led to a foreland basin on the eastern side of the orogenic belt (Liu and Nummedal 2004). The lithospheric flexure due to the sediment loading and the load of the thrust sheet controlled the depth of the basin and the eastern extent to which it reached. The foreland basin, now lower in elevation, was flooded by seawater from Northern Canada to the Gulf of Mexico (Kauffman 1977). Throughout the mountain building event, the narrow zone of foredeep subsidence of the early middle Cretaceous was widening into a much broader zone of

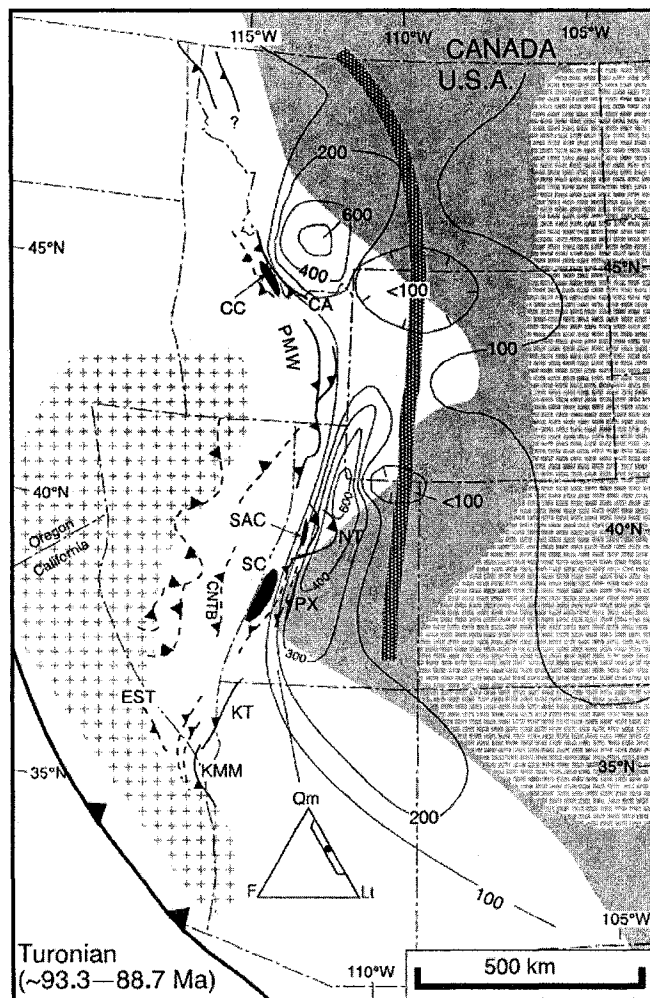


Figure 3.— Illustration of the early foredeep. Tectonic thrusting and lithospheric loading created a deep but narrow foredeep. (from DeCelles 2004)

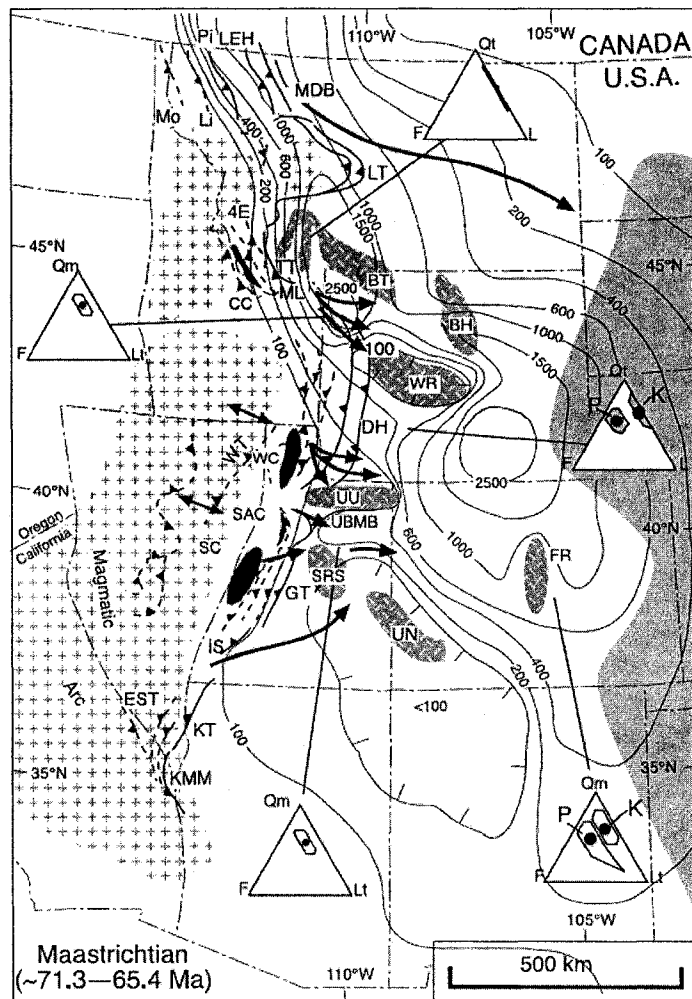


Figure 4.— Illustration of the evolution of the broader foreland basin. The shallowing of the Farallon plate initiated dynamic subsidence, further broadening and drawing down the lithosphere. (from DeCelles 2004)

rapid dynamic subsidence (Fig. 3 and 4, DeCelles 2004). Unlike subsidence due to lithospheric loading, dynamic subsidence is a result of mantle convection drawing the lithosphere down. In concurrence with the dynamic subsidence, the Laramide structures were starting to rise (DeCelles 2004). Thick-skinned tectonics between the Farallon plate and North American plate led to the Laramide deformation and creation of separate smaller basins, such as the Bighorn Basin (DeCelles 2004). Furthermore, at the beginning of the foreland basin formation, the subduction of the Farallon plate resulted in thin-skinned thrusting and folding (the Sevier event; Wiltschko and Dorr 1983; Cross 1986). This gave way to the more vertical movement of the crust, uplifting the fault-bound block of the foreland basin creating smaller separate basins (Laramide Orogeny). The change in crustal deformation has been attributed to the reduction in angle of the subduction of the Farallon plate (Cross 1986).

The focus in this thesis is on the Campanian Eagle Formation, where it is exposed in the southern Bighorn Basin, a Laramide successor basin. The Eagle Formation has recorded the transition from Sevier to Laramide mountain building. This area is an excellent location to look at the relationships between sea level changes and tectonic rectification because during the mountain building events, eustatic fluctuations were also occurring. A detailed history of the interaction between eustasy and tectonism is well preserved in the foreland basin and can be examined in large segments due to the uplifted blocks. Furthermore, numerous studies in this area provide abundant literature on its stratigraphy, which can be used to identify the best locations to collect the data. This led to needed observations to address the conflicting interpretations of previous authors and

AGE	STAGE	GROUP	FORMATION	FACIES ASSOCIATION	AGE(ma)	AMMONITE ZONE
C R E T A C E O U S	C A M P A N I A N	M E S A V E R D E	TEAPOT	ESTUARINE	76 Ma	<i>Bacculites Scottii</i>
			JUDITH RIVER	DELTAIC	79.5 Ma	<i>Bacculites obtusus</i>
			CLAGGETT	OFFSHORE/ OPEN SHELF	80.54 (+/- 0.55) Ma	<i>Bacculites Sp (weak ribs)</i> <i>Bacculites Sp (smooth)</i>
			EAGLE	DELTAIC	83.1 (+/- 0.5) Ma	<i>Scaphites hippocreplis 2</i> <i>Scaphites hippocreplis 1</i>
		CODY	CODY	OFFSHORE/ OPEN SHELF		

Figure 5.— Stratigraphy of the Mesaverde Group within the Bighorn Basin. Depositional environments and precise radiometric dates and relating ammonite zones are also laid out. (from Fitzsimmons and Johnson 2000)

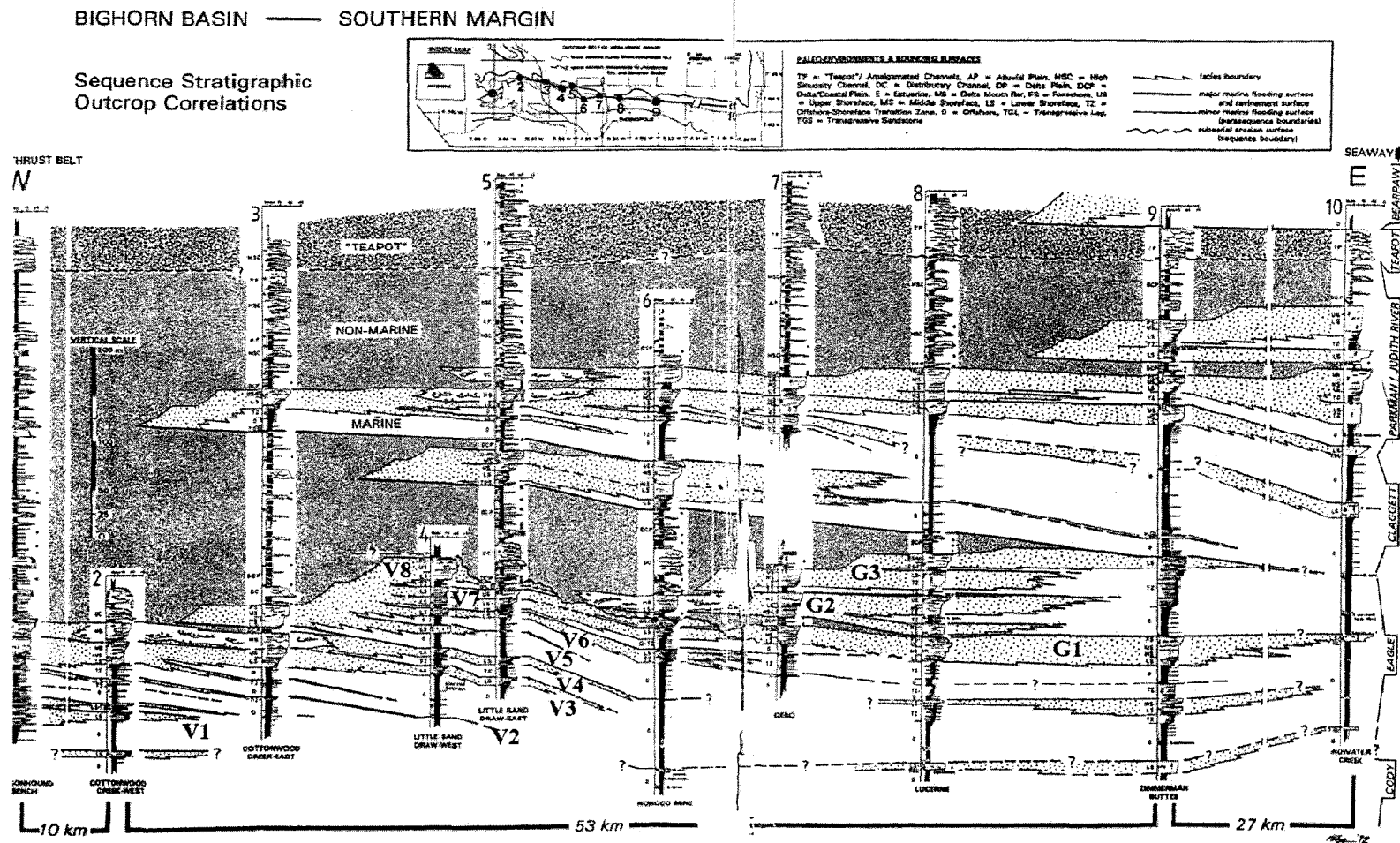


Figure 6a.— Klug's stratigraphic model of the Mesaverde Group. The Gebo member has been interpreted in several different ways. Klug (1993) does not differentiate between the Gebo and Virgelle Members. He sees four Prograding shore sands (G, H, I, J) stacked around a core of terrestrial shale. He describes the sands within the terrestrial shale as lenticular, and does not attempt to distinguish bodies within the terrestrial shale. (from Klug 1993)

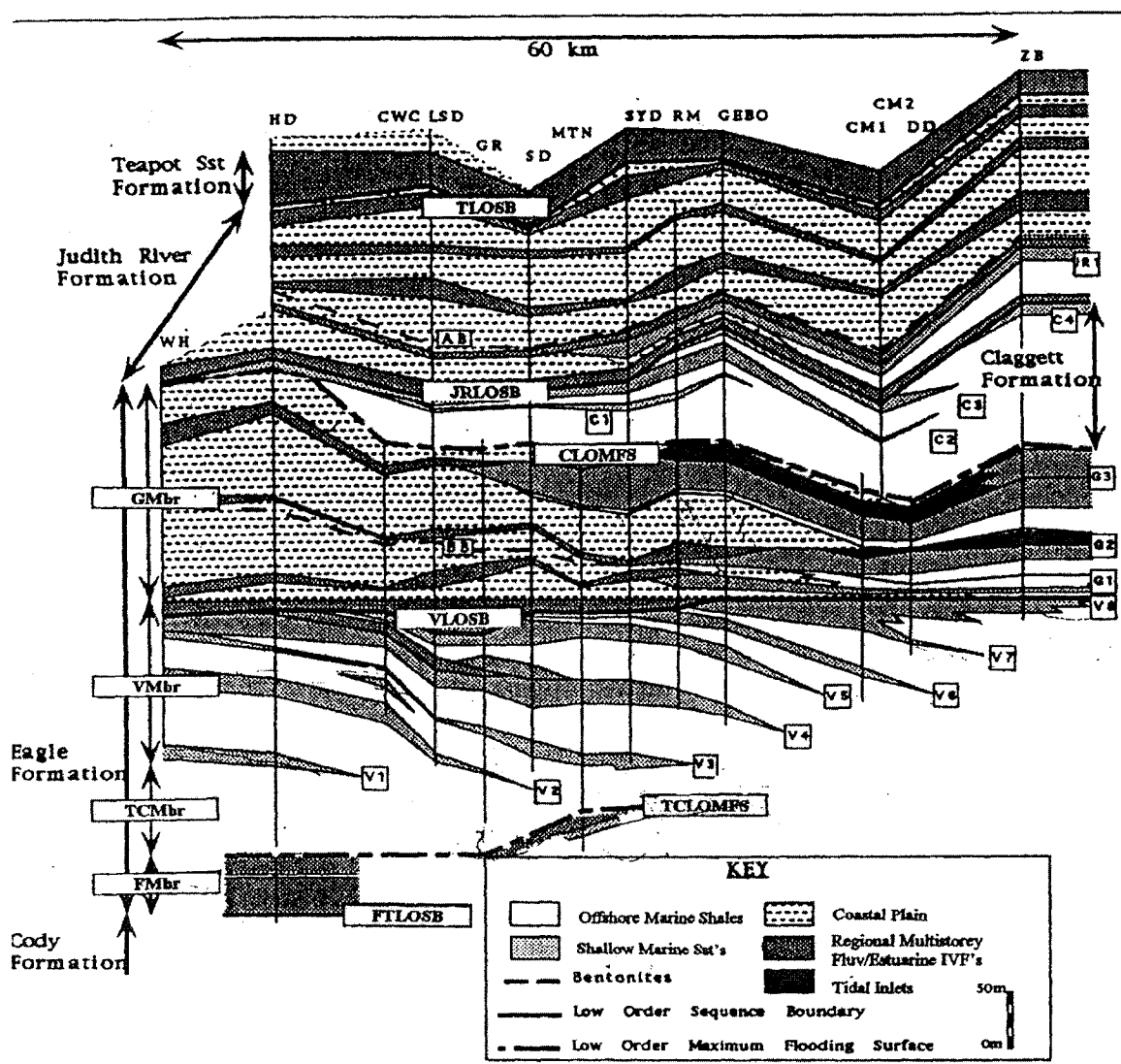


Figure 6b.— Fitzsimmons and Johnson's stratigraphic model of the Mesaverde Group. Fitzsimmons and Johnson (2000) describe 3 Gebo sandstone tongues that they see as extending through the core of terrestrial shale. FMbr, Fish Tooth member; TCMbr, Telegraph Creek member; VMbr, Virgelle member; GMbr, Gebo member. WH, Wagonhound Draw; HD, Hamilton Dome; CWC, Cottonwood Creek; GR, Gloin Reservoir; SD, Sand Draw; MTN, Mountain; SYD, Syncline Draw; RM, Ronoco Mine; Gebo; CM1, Cowboy Mine 1; CM2, Cowboy Mine 2; DD, Double Draw; ZB, Zimmerman Buttes. (from Fitzsimmons and Johnson 2000)

to evaluate the presence or absence of tectonic rectification within the Bighorn Basin.

STRATIGRAPHIC ARCHITECTURE OF THE EAGLE FORMATION

General

The Bighorn Basin is a smaller basin separated from the Western Interior foreland basin that was developed during the orogeny. In the Bighorn Basin, the Mesaverde Group is divided into two sections (Fig. 5). The upper section is designated the Judith River Formation and the lower section the Eagle Formation. Marine shale (Claggett shale) separates the two sections (Fig. 6a). These Formations record regressive -transgressive cycles within the basin (Severn 1961; Miller et al. 1965; Gill and Cobban 1973). Such sedimentary piles that wedge out and become finer-grained basinward can be described as “clastic wedges” (King 1959). The Eagle Formation in turn contains the Virgelle and Gebo members and is well exposed along the east-west trending Mesaverde escarpment of the Southern Big Horn basin.

A detailed geochronology has been worked out for the Mesaverde group using western interior index ammonites (Gill and Cobban 1973; Krystinik and DeJarnett 1995, Fig. 5). Ammonites are useful tools for biostratigraphic dating because of their macro-fossil size, they are a pelagic animal and are not limited to a specific environmental facies, they evolve rapidly, and they were abundant throughout the intercontinental seaway. Additionally, K/Ar-dated bentonite layers are also available for this area (Obradovich 1993).

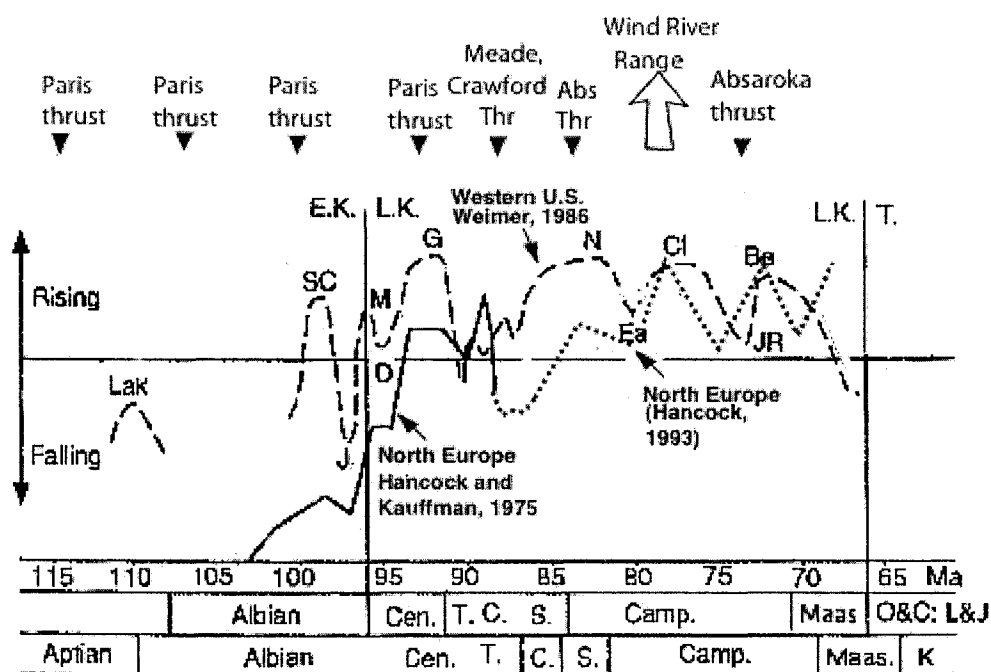


Figure 7.—Sea level Curves from the Western Interior Seaway and Europe. Compared with the tectonic history of the central Rocky Mountains. Abbreviation for stages: Cen.= Cenomanian, T.= Turonian, C.= Coniacian, S= Santonain, C=Campanian, M= Maastrichtian. Two commonly used time scales for the western interior are compared (O&C = Obradovich and Cobban, 1975; L&J= Lanphere and Jones, 1978; K= Kauffman, 1977). Formation name abbreviations are: Lak= Lakota, SC = Scull Creek, J&D=(members of the Muddy SS), M= Mowry, G=Greenhorn, N= Niobrara, Ea= Eagle, Cl= Claggett, JR= Judith River, Be= Bearpaw. From Jordan, 1993; after Weimer, 1986. The Campanian portion of curve for the western interior has been replaced by the newer values of Hancock 1993 (dotted line). (from Swift and Johnson, in review)

Correlating these ammonite and bentonite indicators provide a solid chrono- and biostratigraphic basis for this study of the Bighorn Basin stratigraphy. These units were deposited 83.1- 80.5 million years ago. Sea level fluctuations during the same time period have also been recently studied. Weimer (1984) and Hancock (1993) infer through Figure 7 that the sea level during the evolution of the Bighorn Basin was going through several oscillations punctuated by tectonic thrusting events leaving a shoreline regressive-transgressive complex.

The Eagle Formation has been interpreted as a deltaic succession. It has prograded eastward into the basin as a clastic wedge composed of stacked fluvial plain and strandplain intervals (Fitzsimmons & Johnson 2000). Klug (1993) and Fitzsimmons and Johnson (2000) present detailed stratigraphic models of the Eagle formation that show differences in stratigraphic architecture between the Virgelle and the Gebo members. The models differ in the manner in which the sandstone tongues of the Virgelle and the Gebo are designated. Therefore, I have tried to minimize the confusion by renaming Klug's tongues using the style of Fitzsimmons and Johnson (2000) (Fig. 6a and b). More architectural differences between these models will be discussed later.

Virgelle member

The Virgelle Member, the lower portion of the Eagle Formation, consists of eight tongues. I refer to them as the V1 through V8 tongues. The Virgelle tongues are middle to lower shorefaces deposits that record shallowing upward sequences that offlap eastward into the Bighorn Basin and are interbedded with marine shales (Cody

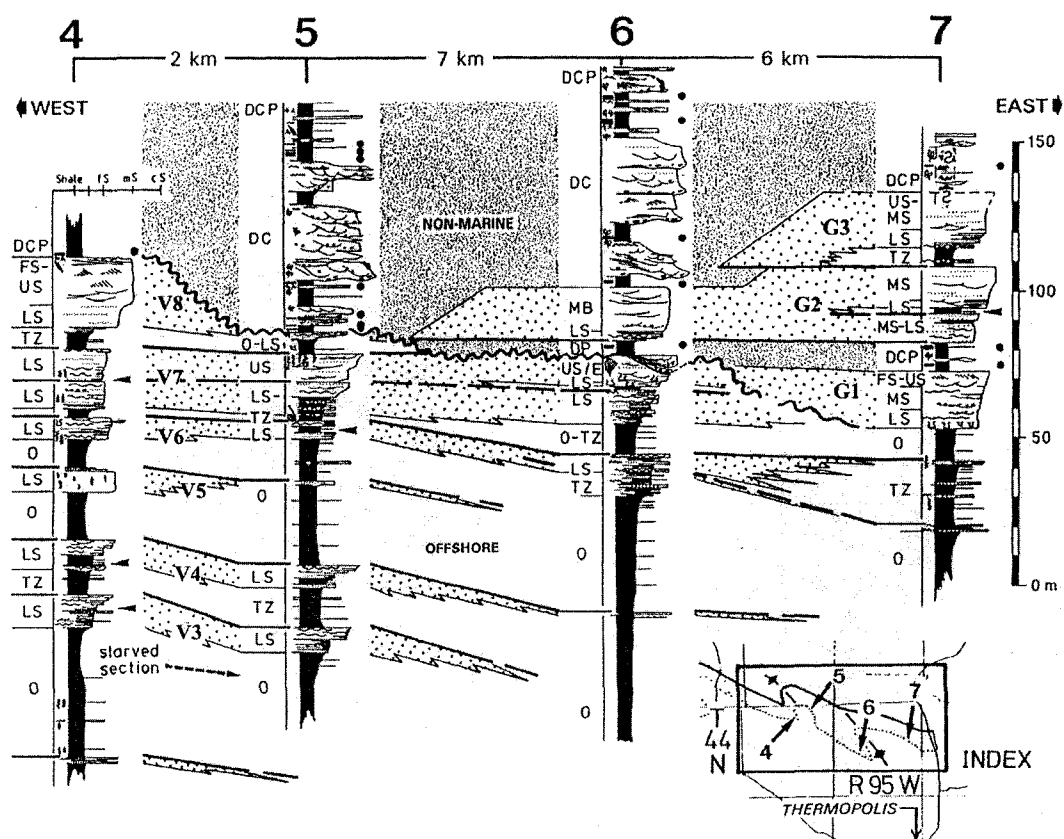


Figure 8.— The Shannon Surface and the Virgelle tongues. Below the unconformity, the sharp-based Virgelle tongues prograde eastward into the basin at a relatively steep angle. Conversely, above the unconformity the Gebo tongues create a thick expanded section with little to no dip. (from Klug 1993)

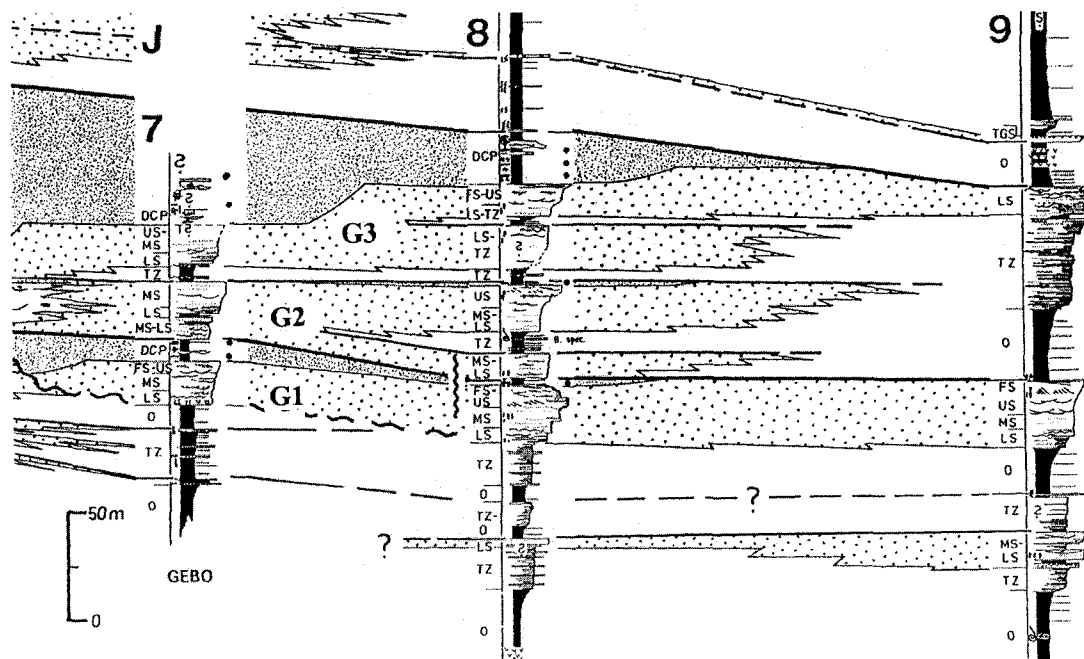


Figure 9.— Expanded tongues of the Gebo formation. Increased sediment input contended with sea level rise during a transgressive shoreline movement creating several expanded tongues within the Gebo formation. (from Klug 1993)

shale, Fig. 5; see Rice and Shurr 1983; Thorne and Swift 1991; Klug 1993). The upper shoreface facies is missing and seems to be truncated by a major erosional surface. However, all tongues can be traced westward to the amalgamation into the strandplain system (Klug 1993). The greater part of the beds consist of classic middle and lower shore face facies, with cross-stratification, hummocky cross-stratification, climbing ripples and occasional rip-up clasts. Virgelle bed thicknesses range from a few meters thick to several centimeters. The majority of the tongues have relatively steep dips (1-2 degrees), eastward into the basin (Fig. 8). One tongue (V4) is depicted as preserving an incised valley that occurred during sea level fall (Fitzsimmons and Johnson 2000). These cyclic sandstone beds are presumed to be a result of multiple eustatic sea level fluctuations, possibly linked to Milankovitch cycles (Klug 1993; Johnson 1995).

Gebo Member

The Gebo Member, the upper portion of the Eagle Formation, overlies the Virgelle Member. They are labeled G1-G3. Two main architectural styles are present. The up-dip Gebo has been interpreted as a succession of shallow, deltaic, coastal plain deposits in which migrating channels transported sediments to the shoreline (Rice and Shurr 1983; Klug 1993; Fitzsimmons and Johnson 2000). The resulting deposit consists of shore-normal channel sands ("shoestring sands"), overbank shales with crevasse-splay deposits, and an abundance of coal. As such, the Gebo Member constitutes an expanded section relative to the succession of Virgelle tongues beneath. Klug (1993) does not resolve these channel sands in his cross-section (Fig. 6a) but the

Fitzsimmons and Johnson (2000) cross section (Fig. 6b) portrays three terrestrial Gebo sands, which they describe as incised valley fills. In a second architectural configuration, shore-parallel strandplain sands further east (basinward) are separated by marine shale (Fig. 6a). These marine sandstones are much more massive than the thin Virgelle sandstones and are much less steeply dipping (.05-1 degree). In Klug's cross-section (Fig. 6a) these strandplain sands fringe the terrestrial core of the clastic wedge, appearing above, below, and at its tip. In the Fitzsimmons and Johnson cross-section however, these margin sand bodies are seen as extensions of those within the clastic wedge (Fig. 6b).

SIGNIFICANCE OF THE ARCHITECTURAL CONTRAST

The differences in stratigraphic architecture of the Virgelle and the Gebo may be due to differential rates of basin subsidence and sediment input verses the rate of sea level rise or fall. The Virgelle was initially described as a low-order falling stage deposit with sequences steadily prograding into the basin (Fitzsimmons and Johnson 2000). Moreover, the Weimer-Hancock curve (Fig. 7) suggests that the Virgelle was deposited during a low-order sea level fall. The Virgelle may therefore be described as a falling stage systems tract produced by an oscillatory sea level fall in which the low order component of sea level change was modulated by high order cyclicity. This pattern has recently been described by Plint and Nummedal (2000) and adapted to the Virgelle by Fitzsimmons and Johnson (2000) in the same volume.

By Gebo time, the sea level was undergoing a relative rise (Hancock 1993; Weimer 1984; Hancock and Kauffman 1979; see Fig. 7). The stacking pattern of the marginal sandbodies (best seen in Klug's cross-section, Fig. 6a) is aggradational to backstepping. The depositional controls must have changed between the last high order sequence boundary on the upper surface of the eighth tongue of the Virgelle and the first tongue of the Gebo in order to so markedly modify the stratigraphic architecture.

Thus the Gebo 1) is much thicker than the Virgelle member, 2) has an aggradational stacking pattern, in contrast to the offlapping pattern of the Virgelle, 3) has significantly gentler dips than the Virgelle, and 4) has retained the transitional section where the shales are subaerial overbank deposits. These observations lead us to the surmise that the Gebo is an expanded section, relative to the Virgelle. Both the rate of creation of accommodation and the rate of sediment input must have been high in order to create Gebo's architecture. If the Gebo is such an expanded section, might it have been rectified? If so, as relative sea level rose in this scenario, sediment input would have generally kept pace, while high frequency sea level falls would appear as episodes of reduced rise and progradation.

HYPOTHESIS

In consideration of these initial observations, I offer the following hypothesis. I suggest that the Gebo deposition was characterized by intensified sediment input

during a variable-rate rise of sea level (pulsed rise) that was rectified by tectonism, resulting in the loss of the high order sea level falls; whereas in the Virgelle, tectonic rectification was absent during an oscillatory sea level fall.

This hypothesis leads to the following testable predictions:

Prediction 1: Thickness of high frequency tongues

The factors that control the thickness of the sandstone beds, sediment flux, sea level rise and fall, and basin accommodation fluctuated between the two formations. On a time-averaged basis there would have been much more sediment bypassing in the Virgelle due to decreasing basin accommodation, creating the thin prograding sandstone tongues. The Gebo, in contrast, because of the increasing accommodation, would have been more efficient in trapping sediment. If Gebo sedimentation was characterized by a simultaneous increase in sediment input and subsidence, then Gebo channel sands, strand plain sands and overbank successions should individually and collectively be thicker than the equivalent units of the Virgelle Member.

Prediction 2: High frequency architecture: sequences versus parasequences

As history's first sequence stratigraphic investigations began, stratigraphers noted basic structural differences between high frequency and low frequency sequences. Low frequency sequences are bounded by subaerial unconformities cut by sea level falls and are separated by internal boundaries into systems tracts. High frequency sequences are commonly bounded by flooding surfaces, formed by sediment starvation during accelerated sea level rise, and generally consist of simple,

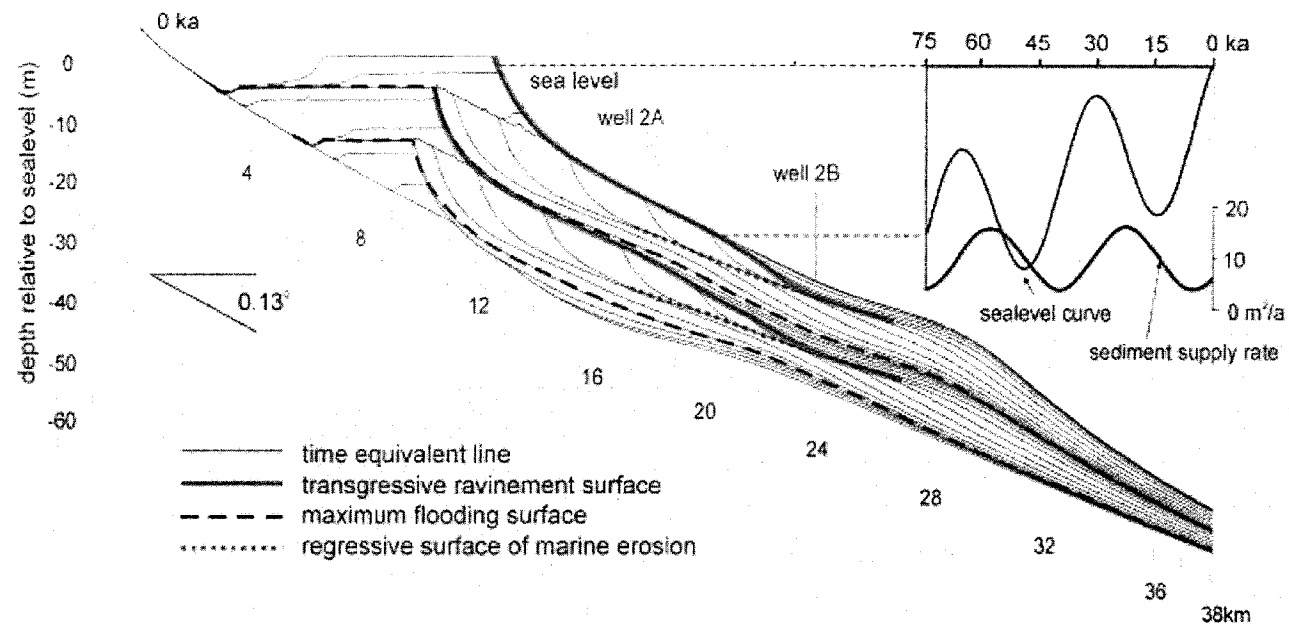


Figure 10a.— Two numerically modeled high-frequency sequences spanning over a 75 kya period. Upper drawings are taken during a 15 kya interval and the lower drawing is the final stratigraphic record. Note the oscillating sea level and sediment supply inputs used during this model and the bounding unconformities formed. (from Storms and Swift 2003)

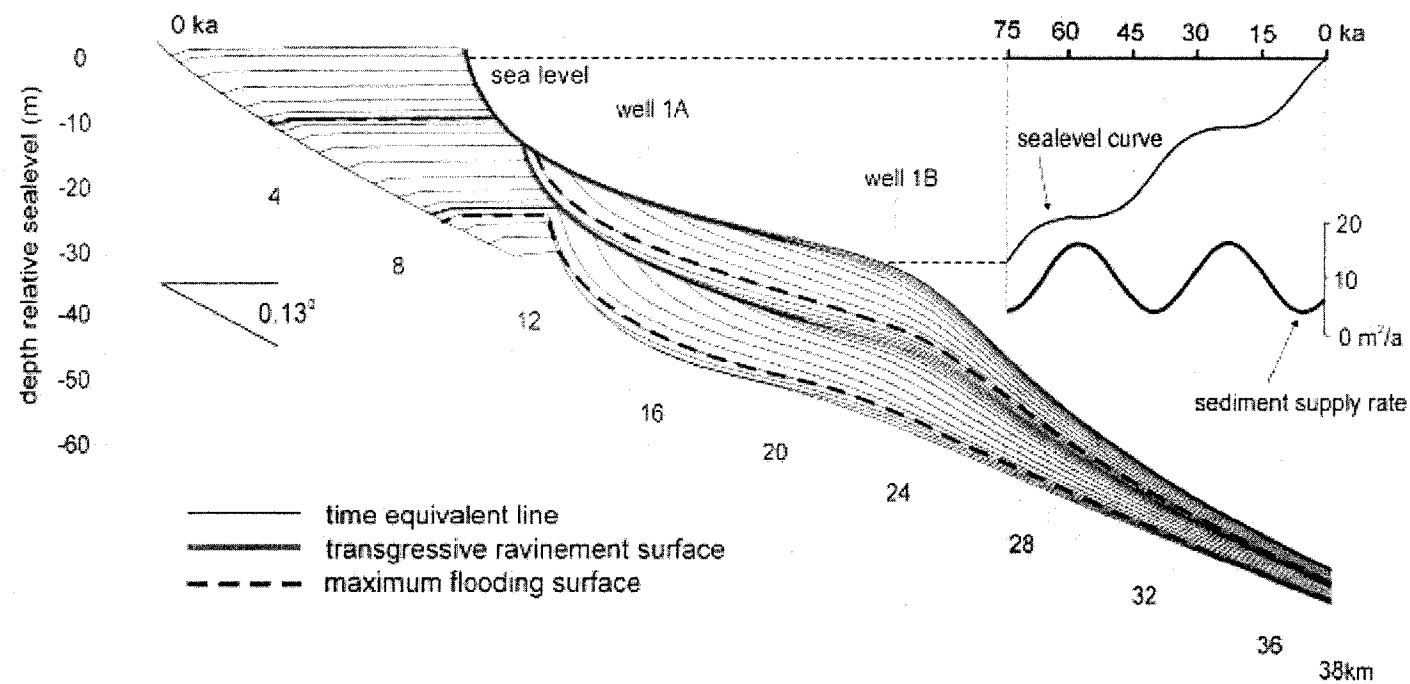


Figure 10b.— Two numerically modeled parasequences spanning over a 75 kya period. Upper drawings are taken during a 15 kya interval and the lower drawing is the final stratigraphic record. Note the different sea level and sediment supply inputs used during this model. The sea level curve is modeling a “pulsing” rise rather than an oscillatory rise. (from Storms and Swift 2003)

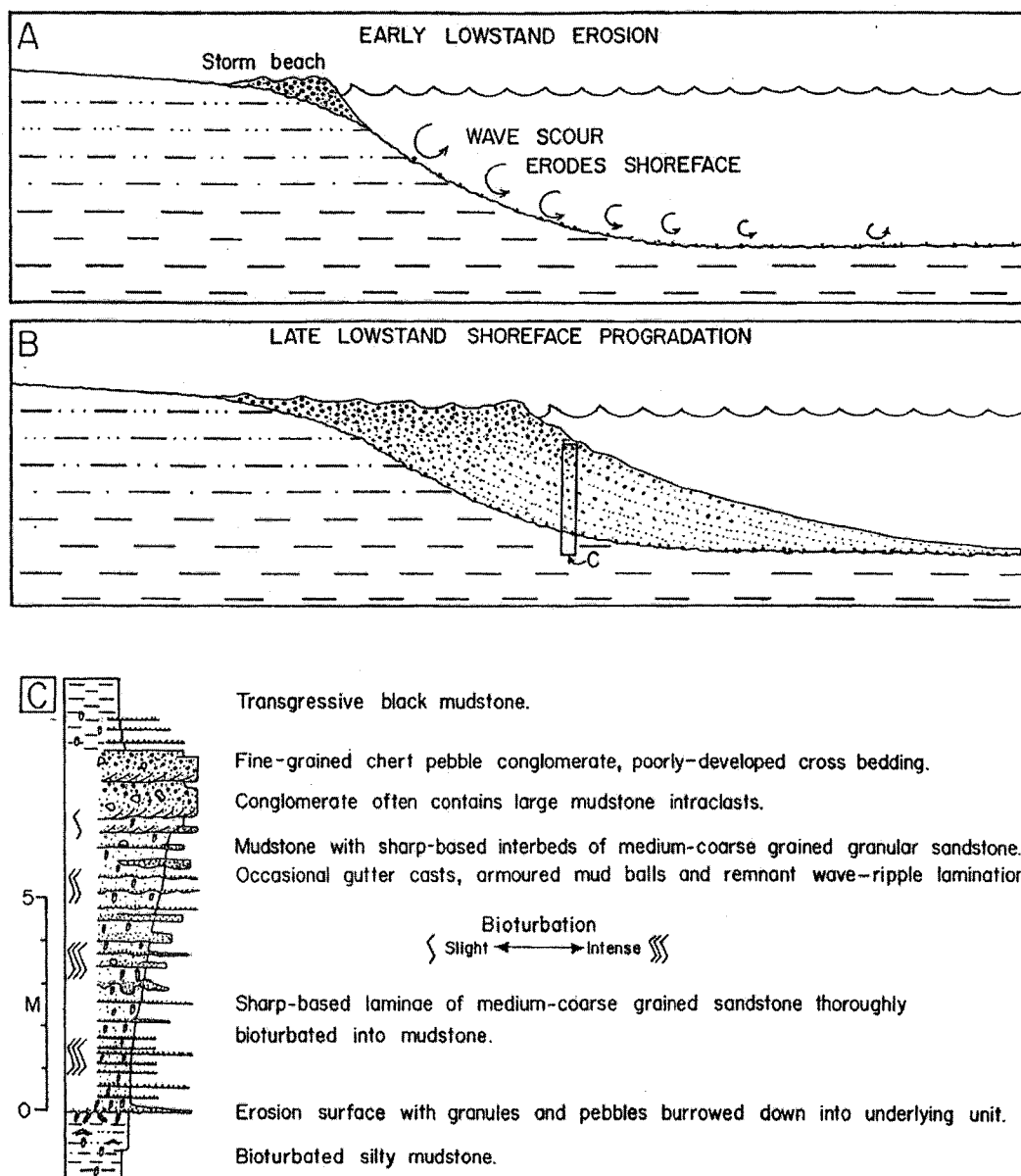


Figure 11.— Creation of an erosional surface during a low stand systems track and shoreline progradation. (from Plint 1988).

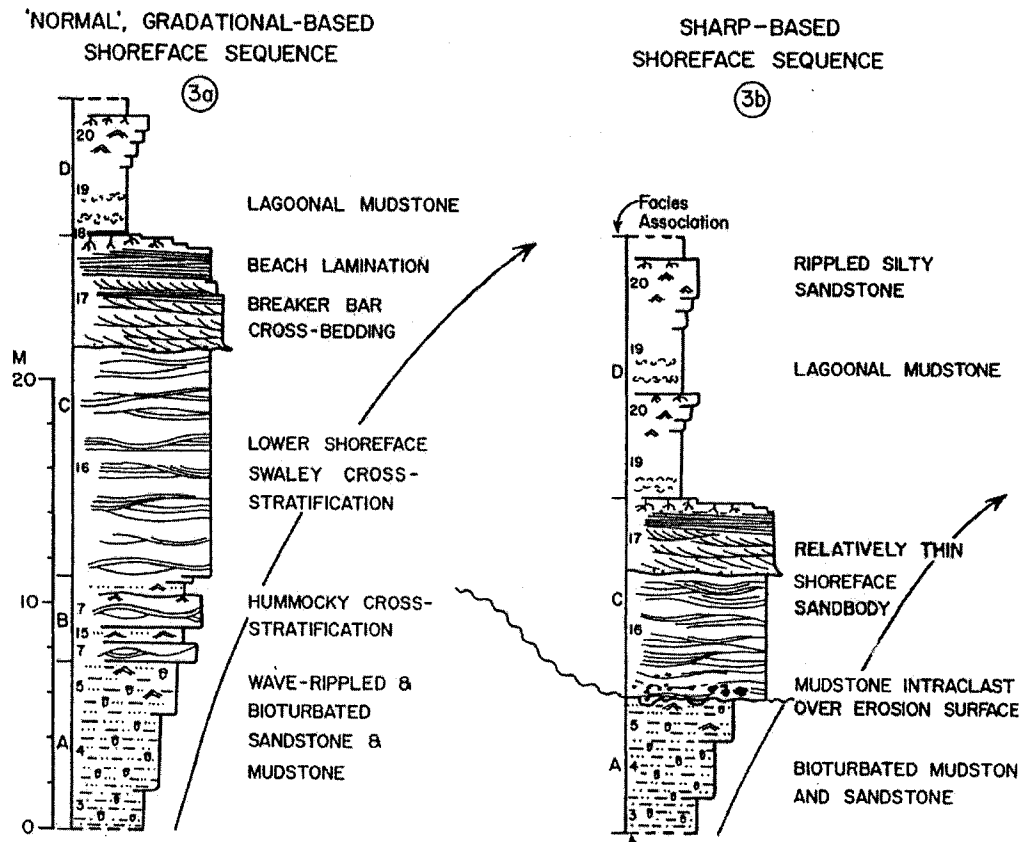


Figure 12.— Gradational-based shoreface sequence (3a) vs. Sharp-based shoreface sequence (3b). The Virgelle Formation is characterized by erosional surfaces overlain by thin sandstones tongues seen in example 3b. (from Plint 1988).

upward-coarsening bed successions. These high frequency beds have been termed parasequences, to distinguish them from “normal sequences” (Van Wagoner et al. 1990). More recently, high frequency sequence sets, formed by high frequency cycles, have also been recognized. They exhibit much of the structure of low frequency sequences. They are bounded by unconformities cut by sea level falls (regressive ravinements, Swift et al. 2003) and maximum flooding surfaces, and are separated internally by transgressive ravinements (Storms and Swift 2003, Fig. 10a and 10b, this thesis). My hypothesis predicts that the Virgelle tongues should contain regressive ravinements, transgressive surfaces, and maximum flooding surfaces (high frequency sequences), while the Gebo tongues should exhibit only binding flooding surfaces and upward-coarsening bed successions (parasequences).

Prediction 3: High frequency architecture: sharp-based shorefaces and gutter casts

Regressive ravinements are evidence of sea level fall, and are characterized by “sharp-based shorefaces” (Plint 1988), often in association with gutter casts. Sharp-based shorefaces contrast with gradational shorefaces showing a progressive, gradual shallowing, marked by coarsening and thickening of beds. Conversely, a sharp-based shoreface does not grade upwards; but begins abruptly over an erosional surface (Fig. 11 and 12). If the rate of sea level fall is greater than the rate of sediment supply, a drop in the wave base will erode the lower shoreface and inner shelf sediments in advance of the prograding upper shoreface sandstones, so that the latter rest directly on inner shelf muds (Plint 1988). Furthermore, Plint (1988) noted in his studies that gradationally based sequences can range from 14 to 18 meters thick, whereas sharp-

based sequences are thinner, as little as 6 meters thick, closely resembling the respective thicknesses of the Gebo and the Virgelle as noted above. The erosional surface or regressive ravinement created by the fall in sea level can be accompanied by structures known as gutter casts. Gutter casts are scours created and preserved on the muddy shelf floor by storm waves or downwelling flows. Because of erosion occurring before the advancing shoreface, soft inner shelf muds are stripped off, revealing stiffer muds with lower water content. During periods of intense storm setup and shoreface downwelling, horizontal, shore-normal vortices cut grooves (“gutters”) into the stiff mud of the inner shelf. The grooves are filled with the overlying hummocky, laminated, fair-weather sandstones (Plint and Nummedal 2000). By locating the regressive ravinement and gutter casts, one may infer that the inner shelf was undergoing erosion during a high-frequency sea level fall (Plint and Nummedal 2000). My hypothesis predicts that the Virgelle member should exhibit sharp-based shorefaces and gutter casts, while the Gebo should not.

Prediction 4: Gradients of high frequency tongues

Deltaic coastal plains are formed during free or normal regressions (progradation caused by rate of sediment supply being greater than the rate of accommodation) and are markedly flatter than strand plains formed during forced regressions (progradation caused by relative sea-level fall, Helland-Hansen and Martinsen 1996; Posamentier et al. 1992). Free regressions can reduce the subsiding surfaces to a minimum grade, while the gradient built by forced regression sandstones is relatively steep due to the overstep of the preexisting shoreface. My hypothesis

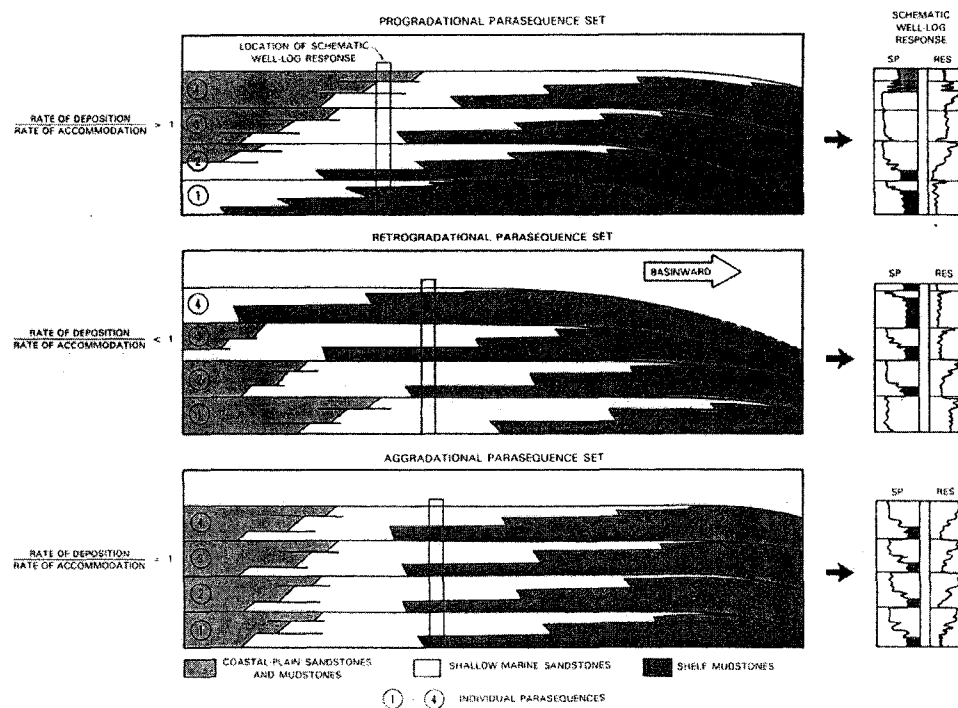


Figure 13.— Parasequence stacking patterns. Illustrated stacking patterns according to the relationship between rate of deposition and rate of accommodation. (from Van Wagoner et al. 1990)

predicts that the Virgelle tongues were deposited during a forced regression, and should be significantly steeper (an order of magnitude) than the Gebo tongues.

Prediction 5: Sequence stacking pattern

The balance between, sediment input and basin accommodation is extremely important in the development of sedimentary stacking patterns. Depending on the ratio of depositional inputs to the basin accommodation, sedimentary sequences can create either progradational, retrogradational, or aggradational patterns (Van Wagnor et al. 1990). Progradational stacking patterns have progressively younger parasequences being deposited further out into the basin. The sedimentary input is larger than the basin accommodation. Retrogradational patterns show the opposite. Its younger parasequences are forced landward. The sedimentary deposition is less than the accommodation being created in the basin. Aggradational patterns have equal or near equal sedimentary inputs and basin accommodation. The younger beds are being deposited on top of one another with little to no lateral shifts (Fig. 13).

The hypothesis derived in this thesis predicts that the Virgelle was deposited during an oscillatory sea level fall, causing the sedimentary input to become greater than the basin accommodation, thus causing the successively younger beds to shift basinward and form a progradational stacking pattern. However, my model also predicts that the Gebo was deposited during a variable-rate sea level rise coupled with an increase of sedimentary input due to an increase in local tectonics. Therefore, the sedimentary input and basin accommodation would have been more or less equal and would have created an aggradational stacking pattern.

Prediction 6: Incised valleys in high frequency tongues

In a sedimentary basin undergoing oscillatory sea level fall, the emerging landscape is progressively incised during the high frequency falls. The areas between the incisions, the interfluvies, become progressively subaerial and create an exposure surface (Van Wagoner et al. 1990). The sediment cut away by the incision bypasses through the channel and is deposited at the lowstand shoreline. The valleys begin to fill during late lowstand and into the transgression starting at the down-dip portion filling with estuarine deposits or by some late stage fluvial progradation (Van Wagoner et al. 1990). During the transgression, increasing tidal channel erosion can remove much of the fluvial fill from the incised valley and cap it with tidal sands leaving the portions of the up dip valley fill younger than the lower area but all are filled prior to the development of the transgressive surface (Fitzsimmons and Johnson 2000). Fitzsimmons and Johnson (2000) report an incised valley fill in a tongue of the Virgelle and also in all of the three tongues of the Gebo that they observed. They noted finding a basal sand and shale sequencing that is interpreted as the estuarine valley fill deposited preceding the transgressive movement. In contrast, my hypothesis predicts that while valley fills are to be expected in the Virgelle, they should be absent in the Gebo.

Prediction 7: Major unconformity

My model predicts that the oscillatory sea level fall that deposited the Virgelle member was followed by a pulsed sea level rise that deposited the Gebo. It necessarily follows that during the transition from Virgelle to Gebo, sedimentation

occurred as a low order lowstand, during which the Virgelle underwent erosion and the up-dip Virgelle underwent extensive erosion. The hypothesis therefore predicts that the two members are separated by a major erosion surface and that significant portions of the up-dip Virgelle member were not preserved.

The information on the previous reports is incomplete or inconsistent regarding the details needed to resolve the above hypotheses. Therefore, we need to revisit these sites to document the existence or absence of the previously described features.

METHODS

In order to address the problem and to test each of these hypotheses, I have undertaken a number of tasks.

Task 1: Compilation of data

I used several main sources of information that document locations and descriptions of their work within the basin including, Fitzsimmons and Johnson 2000; Klug 1993; Gaynor 1991; and Parsons 2001. I used an unpublished base map, obtained from Dr. Donald Swift, of the Mesaverde outcrop area with traverses and columnar sections of each of the traverses from previous field expeditions.

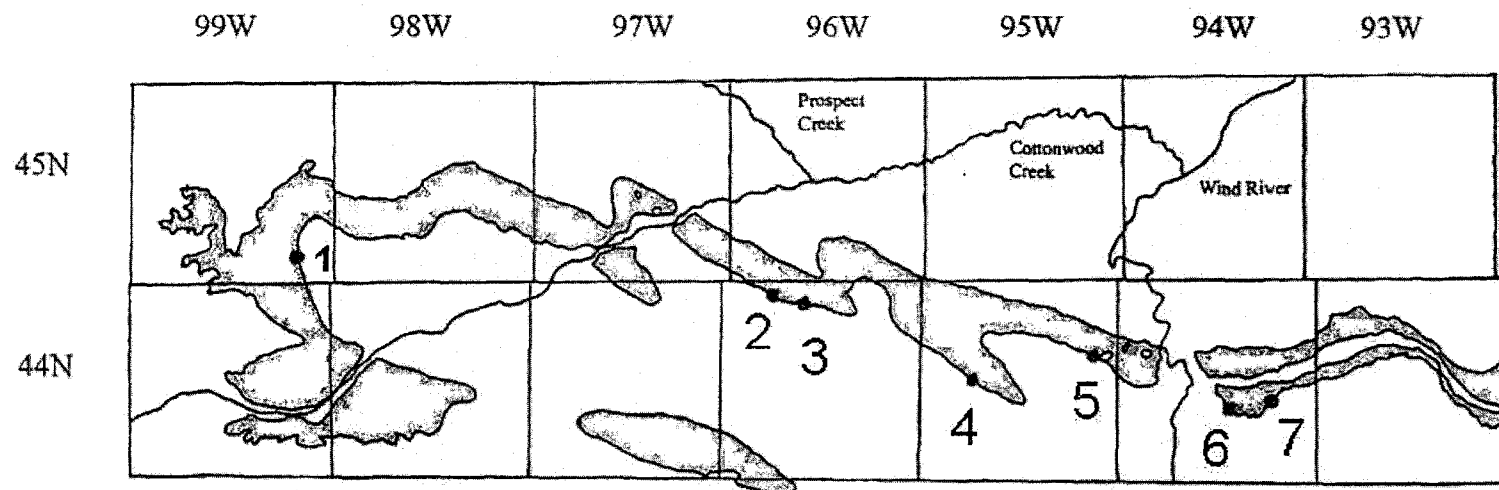


Figure 14.— Outcrop and transect locations. 1) Wagonhound Bench 43 49.68'N, 108 41.32'W; 2) Little Sand Draw 43 48.77'N, 108 24.58'W; 3) Little Sand Draw 43 48.52'N, 108 23.46'W; 4) Ronoco Mine 43 46.30'N, 108 16.72'W; 5) Gebo 43 47.21'N, 108 13.06'W; 6) Cowboy Mine 43 45.44'N, 108 7.42'W; 7) Cowboy Mine 43 46.23'N, 108 6.0

Table 2.— Table of study locations within the Bighorn Basin and the objectives.

Location	Objective
Zimmerman Buttes	Identify sharp-based shorefaces in Gebo
Little Sand Draw	Identify sharp-based shorefaces in Virgelle
	Find gutter casts if present in Virgelle
	Walk along strike of Virgelle to Gloin Reservoir to find incised valley wall in Virgelle tongue #4
	Walk up section to find incised valley wall in Virgelle tongue #4
	Investigate the deltaic architecture of the Gebo
Wagonhound Bench	Identify multistory channel fills in Gebo
Gebo (Kirby)	Walk up section to find incised valley wall in Gebo 2
Ronoco Mine	Walk up section to find incised valley wall in Gebo 1
	Traverse Gebo tongues to Syncline Draw
Any section west of Gebo (Wagonhound, Hamilton Dome, etc.)	Find Gebo tongues
Any section west of Little Sand Draw (Wagonhound, Hamilton Dome, etc.)	Locate large unconformity

Task 2: Preparations before entering the field

- Selections of sections visited in the field were taken from publications and enlarged for easy use in the field.
- Aerial photography of the locations of transects were obtained and printed on high-resolution photo paper in order to more easily view the study area.
- A handheld GPS unit was used and updated with maps and programs to help detail the trip and transect locations.

Task 3: Field work in the Bighorn Basin

I addressed the predictions listed above at multiple locations within the Bighorn Basin by reexamining key outcrops and traverses and by documenting the presence or absence of important sedimentary structures and boundary features (Fig. 14, Table 2).

Zimmerman Buttes: As described, sharp-based shorefaces are signs of sea level fall and have been identified by Fitzsimmons and Johnson (2000) in the Gebo in these sections. According to prediction #3, the Gebo should not have any sharp-based shorefaces due to tectonic rectification, for that reason, it was important to visit this location where sharp-based shorefaces were recognized.

Little Sand Draw: I have predicted that the Virgelle was deposited under an oscillatory sea level fall without tectonic rectification and because of this, evidence of sharp-based shorefaces and gutter casts was sought. Fitzsimmons and Johnson (2000) and Klug (1993) mention such structures in their descriptions. Transects were made across the fourth tongue of the Virgelle member. Here, Fitzsimmons and Johnson see valley incision

among the Virgelle valley wall. At this location I investigated the deltaic architecture of the Gebo, paying close attention to the sedimentology and any type of incision found.

Gebo, Ronoco Mine, and Wagonhound Bench: The predicted (#5) tectonic rectification during the Gebo does not allow any evidence of a sea level fall. Therefore, one should not see any incised valleys in the Gebo. Fitzsimmons and Johnson (2000) identified incised valley fills in all three Gebo tongues. I walked both along strike and up section in order to try and find his proposed valley walls, multistory valley fills and their relationship with the capping marine shoreface.

Wagonhound Bench: The Klug (1993) and Fitzsimmons and Johnson (2000) models differ in that Klug does not recognizing the large unconformity that caps the Virgelle past Little Sand Draw. Fitzsimmons and Johnson (2000) carry the unconformity as far West as Wagonhound Bench. Furthermore, Klug extends the up dip portion of the Gebo tongues only to Ronoco Mine, whereas Fitzsimmons and Johnson (2000) stretch the tongues continuously, to again, Wagonhound Bench. I traversed this section in order to resolve these differences.

RESULTS AND ANALYSIS

Following are the results of the individual predictions previously discussed. Some results were produced from the observations made during field work, when others were the product of the examination of previously published data.

Thickness of high frequency tongues

The first prediction generated by the hypothesis concerns the thickness of the Gebo Member relative to that of the Virgelle Member. If Gebo sedimentation was characterized by a simultaneous increase in sediment input and subsidence, then the Gebo should be thicker than the Virgelle Member, which was deposited during low sedimentation and basin accommodation. In fact, comparisons within each transect measured within the Basin showed that the Virgelle tongues were noticeably thinner than Gebo tongues (compare Fig. 6a and 6b). Field-estimated thicknesses of the Virgelle range from a few meters to possibly several meters thick. However, in a number of locations, the Gebo tongues are estimated to tens of meters thick. More detailed comparison is rendered difficult by the rapid basinward thinning of both units, and by the irregular shape of the Virgelle Member, whose thickness measurements vary drastically as successive tongues are considered up-section (Fig. 6a and 6b).

As noted above, Fitzsimmons and Johnson (2000) propose that the contact between the Virgelle and the Gebo is a major (“third order”) unconformity whose erosional time value increases marginward (Fig. 6a and 6b). If so, the continental portion of the Virgelle may have been lost to erosion, so that the down-dip “marine” portion of

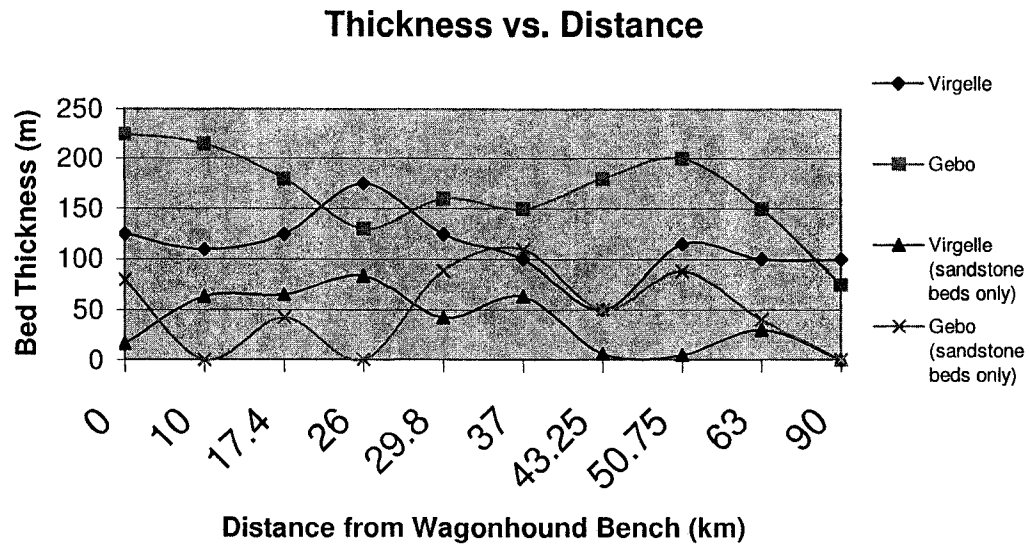


Figure 15.— Bed thickness vs. Distance

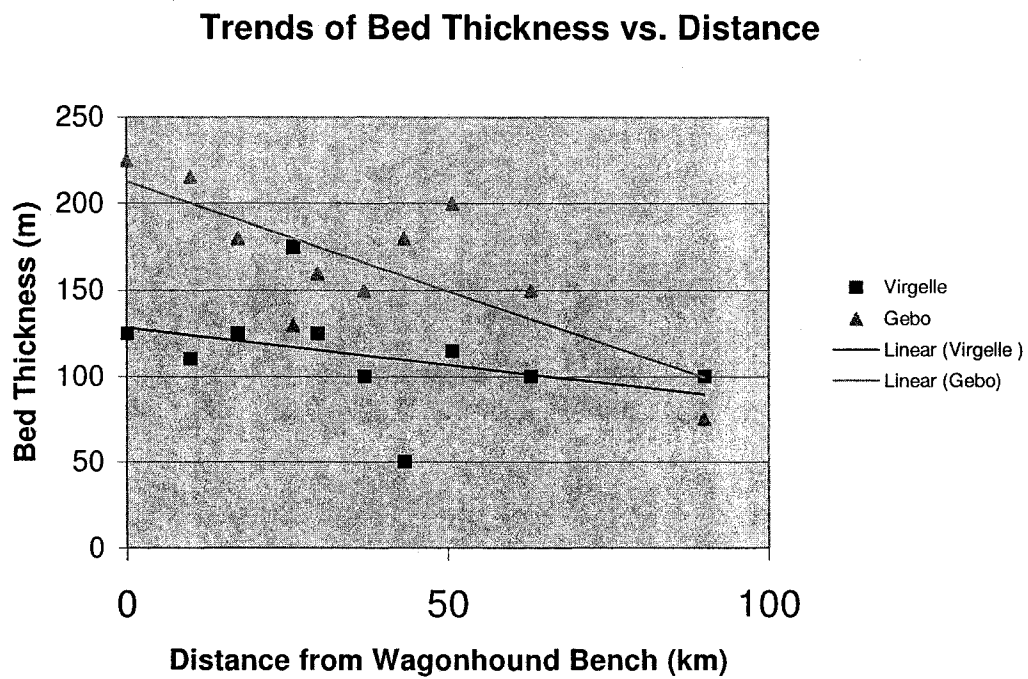


Figure 16.— Bed thickness vs. Distance with trendlines

Separated Trends of Bed Thickness vs. Distance

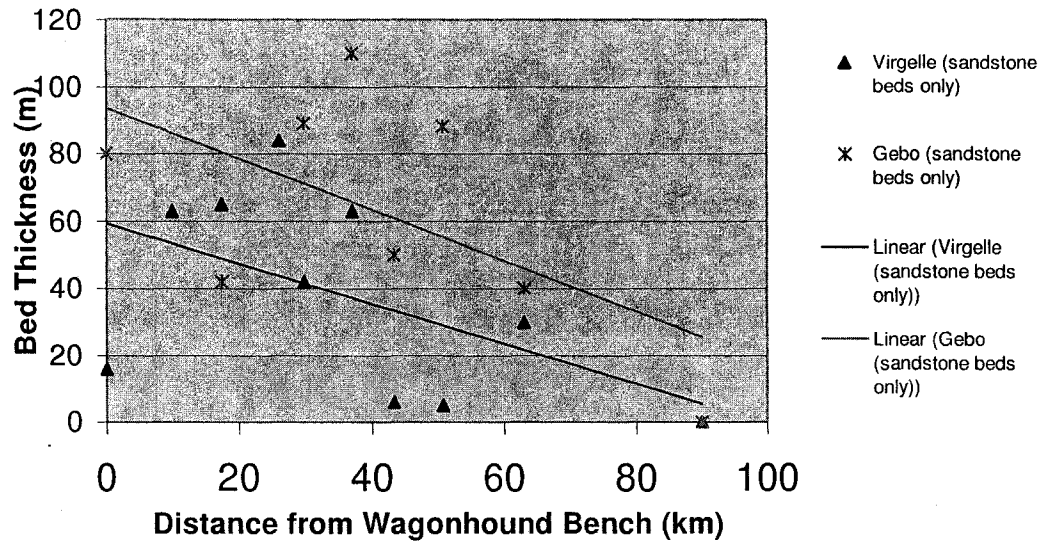


Figure 17.— Bed thickness vs. Distance by separate beds

Thickness vs. Length

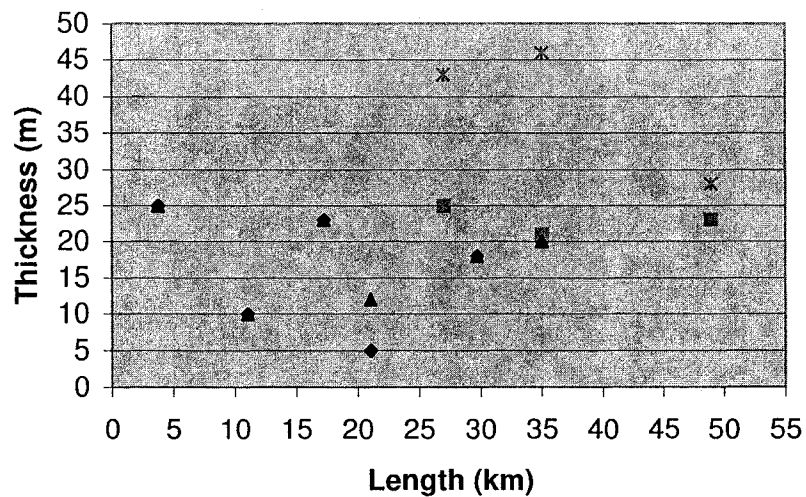


Figure 18.— Tongue thickness vs. Tongue length. Base = the most basal portions of the sandstone tongue was measured; Max. = the thickest portion of the tongue, regardless of location, was measured.

the Gebo may be the portion most comparable to the Virgelle. Nevertheless, it is possible to estimate the relative thickness of the two members from the sections measured by Klug (1993; see figs. 15-18 in this thesis). The figures compare the total thickness of the respective formations at successive measured sections, and also the aggregate thickness of sandstone beds.

Figures 15-18 are graphs of bed thickness, based on Klug's (1993) measurements. The first graph incorporates all four series (two complete formations and two sandstone bed measurements only), whereas Figures 16 and 17 have been separated and has the addition of trend lines. When plotted against one another, the thickness differences between the Gebo and the Virgelle are easily viewed, being that the Gebo is much thicker than the Virgelle. When plotting only the sandstone beds, the same trend is noticed. Exception to the trend is at the furthest up-dip portions of the Gebo where sandstone beds are absent in the measured transects (Fig. 15). The trend lines of the total Gebo and Virgelle thickness (including shales) show a sharper decrease in member thickness of the Gebo than the Virgelle when plotted against distance from Wagonhound Bench, basinward, characterizing their previously described architecture (Fig. 16). Much like Figure 16, the plotting of Gebo and Virgelle sandstone bed thicknesses show a general decrease with distance. However, the trend lines of the two follow a similar slope, unlike the trend lines that include the shale (Fig. 17).

In another estimate of bed geometry, a plot of the thickness of the Virgelle and Gebo sandstone beds (excluding inter-bedded terrestrial or marine shale), against their

length can be considered. A plot of bed thickness, measured in two locations of the bed, the location at which the tongue is the thickest and the location at the most up-dip portion of the exposed tongue, was created. When plotted against the sandstone beds length, the results tend to show two groupings (Fig. 18). The two groups, further described below, indicate two very different depositional environments and architectures. The measurements were generated from the Klug (1993) model (Fig. 6a). In this model, the Gebo distributary sands were neglected. Klug lumps the Gebo sands in with the non-marine, overbank shales. The grouping is beneficial because only the marine Gebo sands are compared with marine Virgelle sand, rather than marine and terrestrial Gebo sands. After analyzing the diagram, two distinct groupings can be seen. The marine Gebo sands show generally a much thicker relationship to length than the Virgelle tongues.

The data from the model (Fig. 18) appear to be well separated into two groups. However, when the data is run through an analysis of variance, the results show differences. The null hypothesis of the t-test or student test is that there is correlation between the data (i.e. for the two sample t -test the two measurements of the rock body thickness are no different). The significance value for the hypothesis test is also set at 95% or $p = .05$. Usually if using a one-in-twenty (0.05) chance of making the wrong decision, an individual is satisfied that there is a statistical significance and rejects the null hypothesis that there is no difference. Presuming that if the t-value for a correlation coefficient test is less than 0.05, it indicates that the correlation coefficient is significantly different from zero (either positive or negative). Therefore, there is some significant amount of linear relationship between the two variables of interest. The t- value for the

Table 3.— Table of thickness measurements calculated by using the t-test.

T-test			
Western most portions of tongues Virgelle vs. Gebo		Thickest point of tongue Virgelle vs. Gebo	
T value	-0.714710325	T value	-3.813903421
P value	0.485763371	P value	0.005134042
Degrees of Freedom	15	Degrees of Freedom	8

measurements taken at the thickest portions of the Virgelle and Gebo were much lower than the threshold for this experiment and therefore rejects the null hypothesis. Therefore, measurements taken at the thickest point of the members pass the test and the data prove to be segregated by thickness. Conversely, the up-dip measurements did not produce numbers that support the model and do not show a difference in grouping; in this case, the null hypothesis holds true (Table 3). Overall, the thickness difference is documented in the field and is supported by the statistical analysis. I therefore conclude that the Gebo tongues are collectively thicker than the Virgelle tongues.

High frequency architecture: sequences versus parasequences

My hypothesis predicts that the Virgelle tongues should contain regressive ravinements, transgressive surfaces, and maximum flooding surfaces (high frequency sequences), while the Gebo tongues should exhibit only binding flooding surfaces and upward-coarsening bed successions (parasequences). Sequences and their boundaries are thought to form in response to cycles of relative fall and rise of sea level (Van Wagoner et al. 1990). The distinction between parasequences and high frequency sequences can be seen better in the contrasting numerical models of Storms and Swift (2003) (Fig. 10a and 10b). If the Virgelle is the product of an oscillatory sea level fall, then its high frequency sequences should reveal full sequence architecture (transgressive ravinement and maximum flooding surfaces). If Gebo sedimentation was characterized by a simultaneous increase in sediment input and subsidence, then full sequence development in its high frequency cycles should be suppressed (maximum flooding surface collapsed onto the transgressive ravinement). In the field, the tongues of the Virgelle generally exhibit full sequence architecture as predicted. Excellent examples exist at Little Sand Draw. The



Figure 19.— Climbing ripples in a Virgelle sandstone storm bed between shale along the Little Sand Draw transect.



Figure 20.— Glossifungites on top of V4 surface. Glossifungites surfaces are abundant throughout the Virgelle. They are interpreted to indicate sea level fall.



Figure 21.— Photograph of a capping flooding surface of the Virgelle and the transgressive sequence leading towards a maximum flooding surface above.

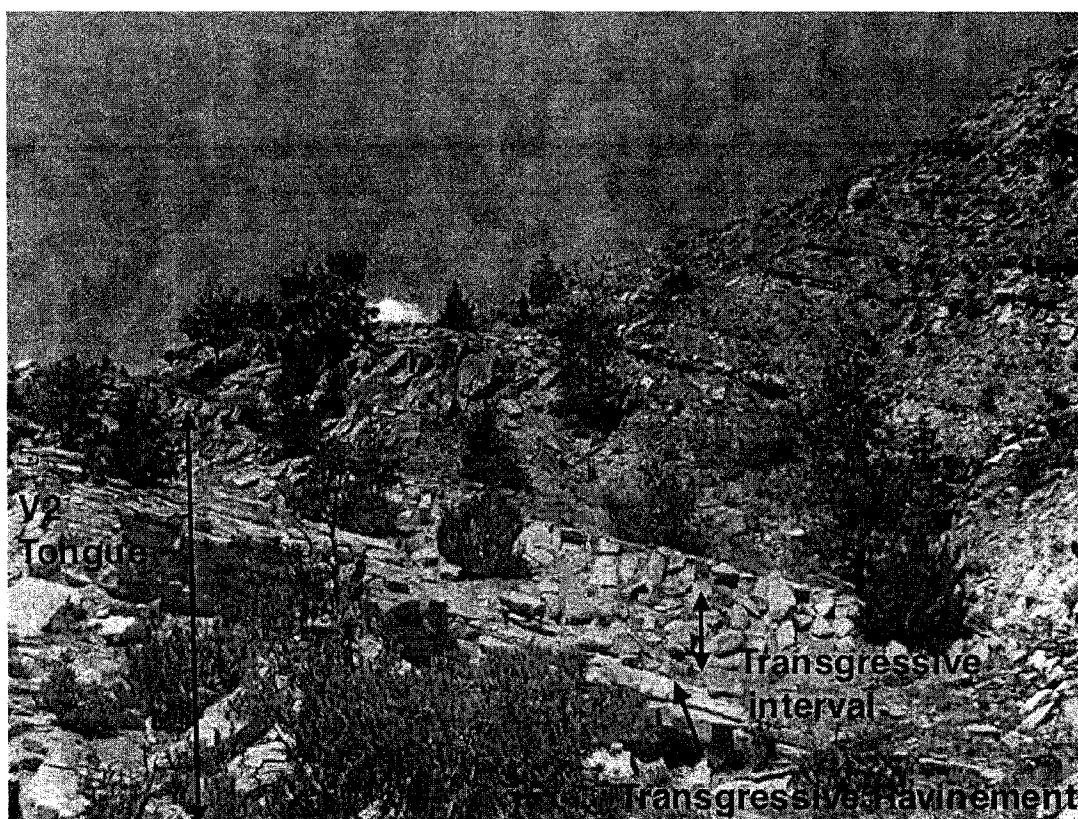


Figure 22.— V2 tongue of the Virgelle showing surfaces of transgressive ravinement and succeeding storm beds. Above the ravinement, a maximum flooding surface can be identified within the overly shales.

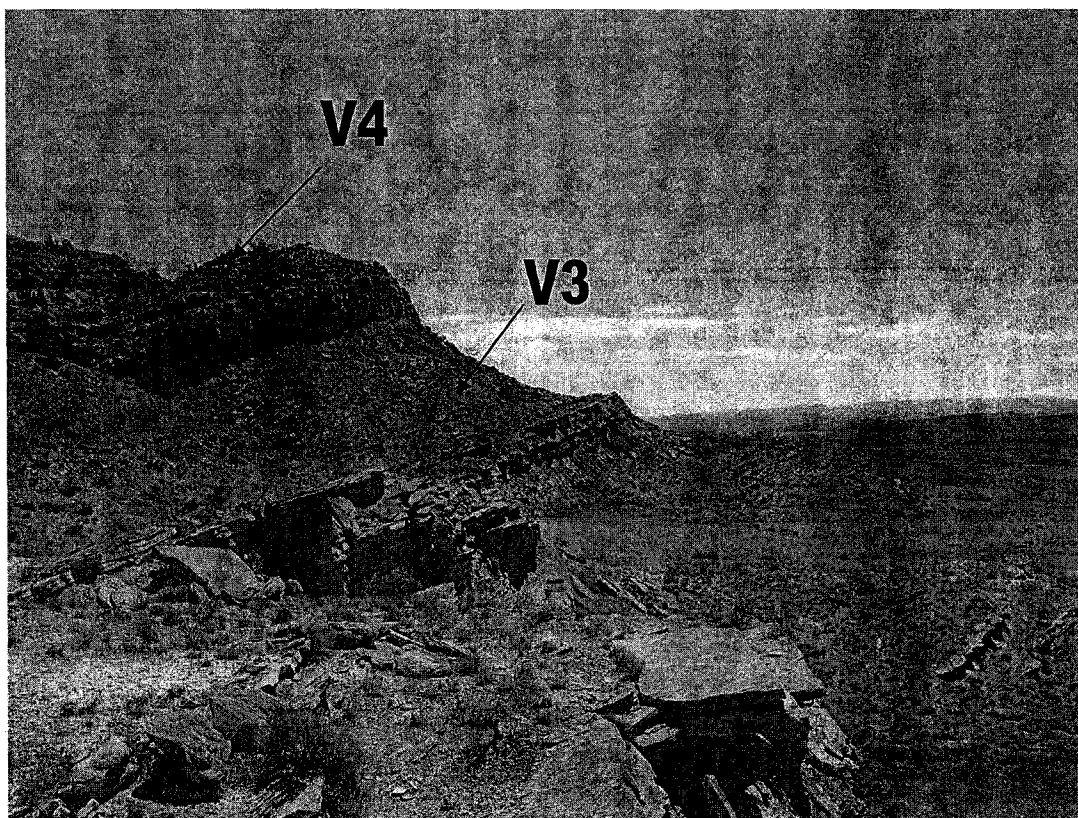


Figure 23.— Little Sand Draw. Looking east, the prominent Virgelle member in the center is V3. Note the well-defined flooding surface capping it, protruding ledge directly under the slope of shale.

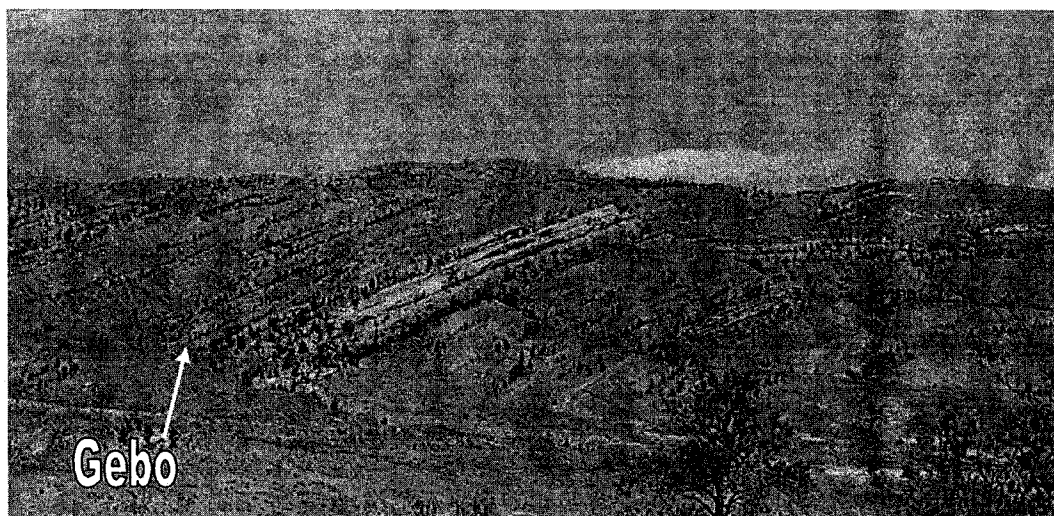


Figure 24.— Wagonhound Bench. Multi-story Gebo sandstone bed separating upper terrestrial shale sequences from lower marine shale sequences.



Figure 25.— Irregular distribution of Gebo terrestrial channel sands at Wagonhound Bench.

Virgelle tongues are typically capped by rippled flooding surfaces (Fig. 19) or with Glossifungites surfaces (Fig. 20). These surfaces do not form the unit boundary but are internal divisions (transgressive surfaces), separating the regressive half sequences from the underlying transgressive half sequences that extend upward for several meters to a maximum flooding surface (Fig. 21). As mentioned above, Glossifungites are a grouping of burrows that are commonly found in stiff, fine-grained sediments of the inter-tidal or shallow marine system and are understood to have formed following a sea level fall and just after the initial transgressive turnaround track (Pemberton and Frey 1985).

These surfaces in the Virgelle may be succeeded by a meter or more of thin, transgressive storm sands alternating with shales (Fig. 22). The surfaces constitute transgressive ravinement surfaces, and the succeeding storm beds constitute a transgressive systems tract. The maximum flooding surface can sometimes be seen higher in the overlying shales, as a change from gray (organic rich) transgressive shale to buff-colored regressive shale (Fig. 23). Thus, as predicted, the Virgelle tongues must be counted as high-frequency sequences rather than parasequences. Fitzsimmons & Johnson (2000) note that true parasequences do appear in the Virgelle, but as higher frequency cycles of one or two meters thickness, in the heterolithic turn-around beds near the tips of the tongues.

The architecture of the Gebo tongues is more enigmatic. The up-dip Gebo, begins with a massive multistory sand body, of probable estuarine origin (Fig. 24), which is overlain by delta-plain shales and “shoestring” distributary sands (Fig. 25). Marine

shoreface sands are embedded along the basinward margin of this terrestrial core, and extend from it into the down-dip shales (Fig 6a). The extent to which Gebo sands are autocyclic (their distribution controlled by random avulsions of rivers) or allocyclic (their distribution controlled by high-frequency sea level fluctuations) is not clear, and must be deferred until other predictions are tested (see below).

High frequency architecture: sharp-based shorefaces and gutter casts

My hypothesis predicts that the Virgelle member should exhibit sharp-based shorefaces and gutter casts, while the Gebo should not. However, interpretation of the base of a sandstone is complicated by the fact that during oscillations, shoreline migration is out of phase with sea level. As a high-frequency sea level begins to slow, shoreline retreat will frequently be reversed to basinward advance before high-frequency highstand is achieved (Posamentier and Vail 1988). Mellere and Steel (2000) has shown that in the lower Mesaverde of the Hanna basin, Wyoming (Eagle Formation equivalent), that as a consequence of this phase lag, a high frequency tongue is sharp-based in the up-dip portions, but gradational further basinward. Furthermore, as described above in prediction 2, gutter casts, when associated with the regressive ravinement, are also used to help identify sea level fall and inner shelf erosion, characteristic of shoreline progradations initiated by sea level falls (Plint and Nummedal 2000). Fitzsimmons and Johnson (2000) documented that the Virgelle tongues exhibit sharp-based shorefaces with gutter casts. Additionally, these authors note that the Virgelle tongues tend to rest with regional disconformity on the underling shale beds and are “sharp-based” in the sense of Plint (1988). They argue that the Virgelle tongues are therefore high-frequency sequences



Figure 26.— Outcrop at Wagonhound Bench, V2. Sharp-based shoreface, thick swaley cross-stratified sandstone abruptly overlying thinly bedded sandstone and mudstone. Rip-up clasts were found within base of capping sandstone bed. The V2 tongue is the only tongue to show sharp-base shorefacing within the Virgelle. Image scale: 3'x3'.

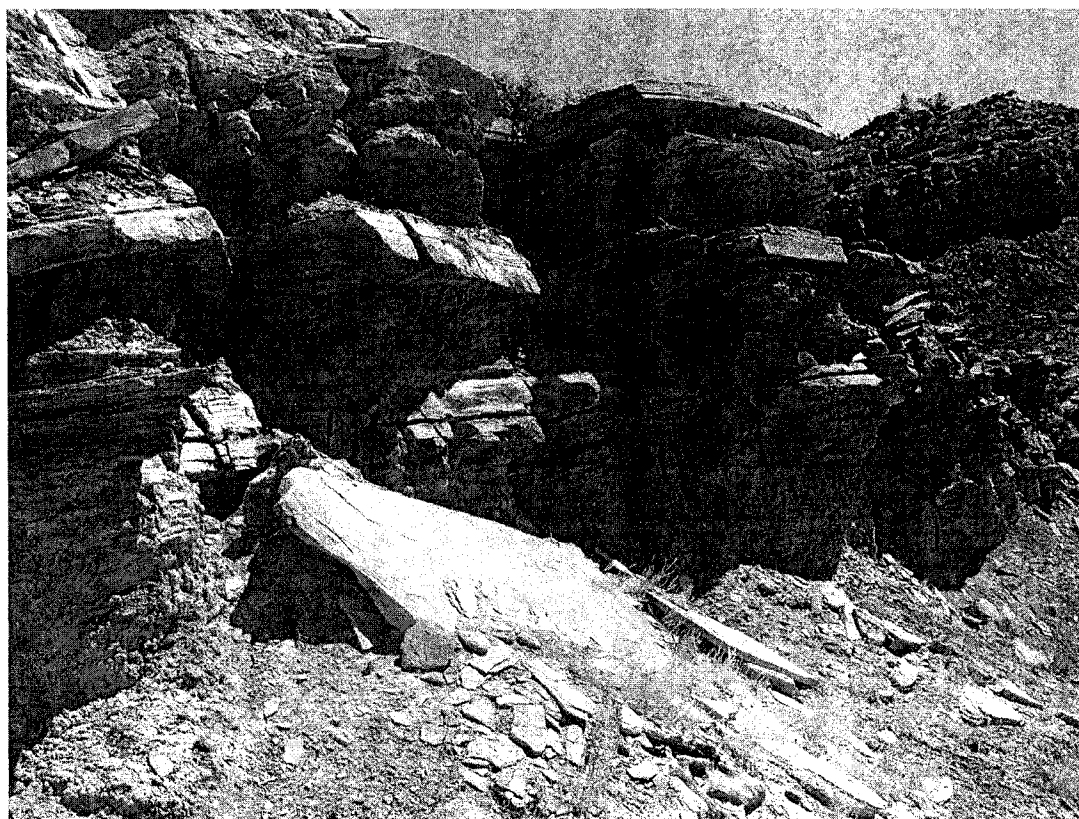


Figure 27.— Little Sand Draw, V3 tongue of the Virgelle. Marine sandstone and shales. Gradational-based sequences steadily coarsen upward from thinly bedded, wave rippled, sandstone into swaley cross-stratified sandstone.

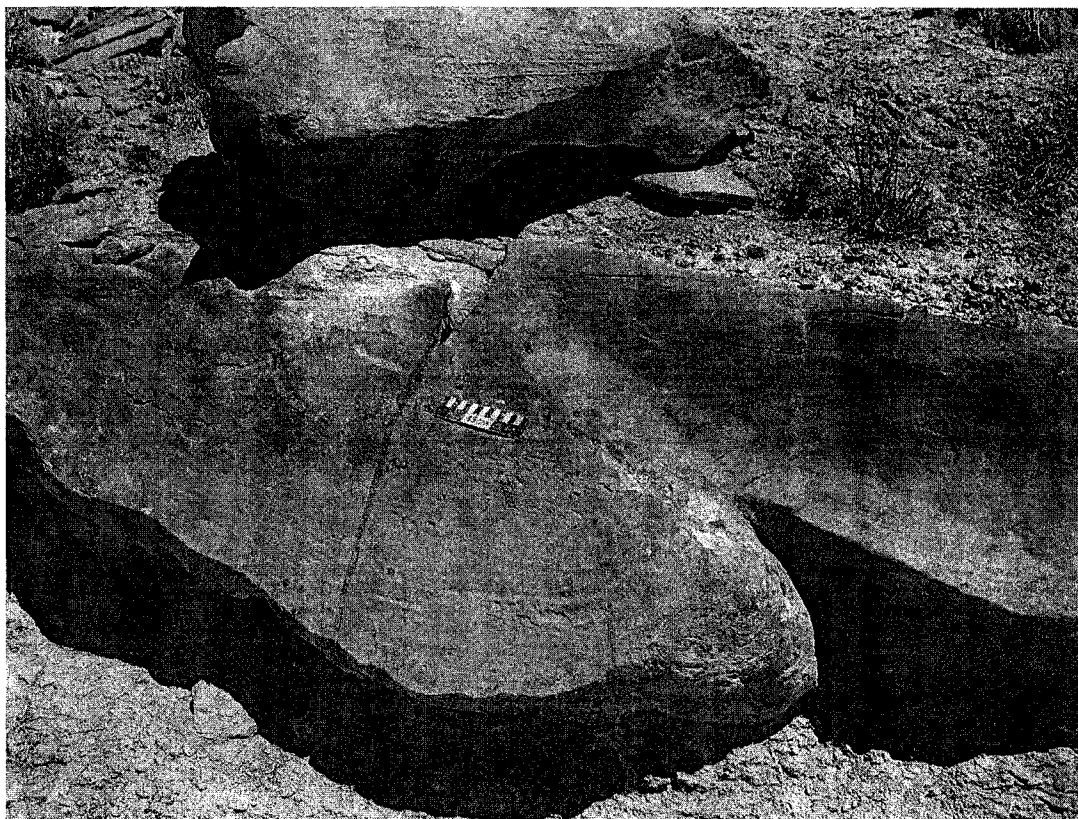


Figure 28.— Gebo gutter cast. Gutter cast seen in cross-section view in the upper Virgelle member.

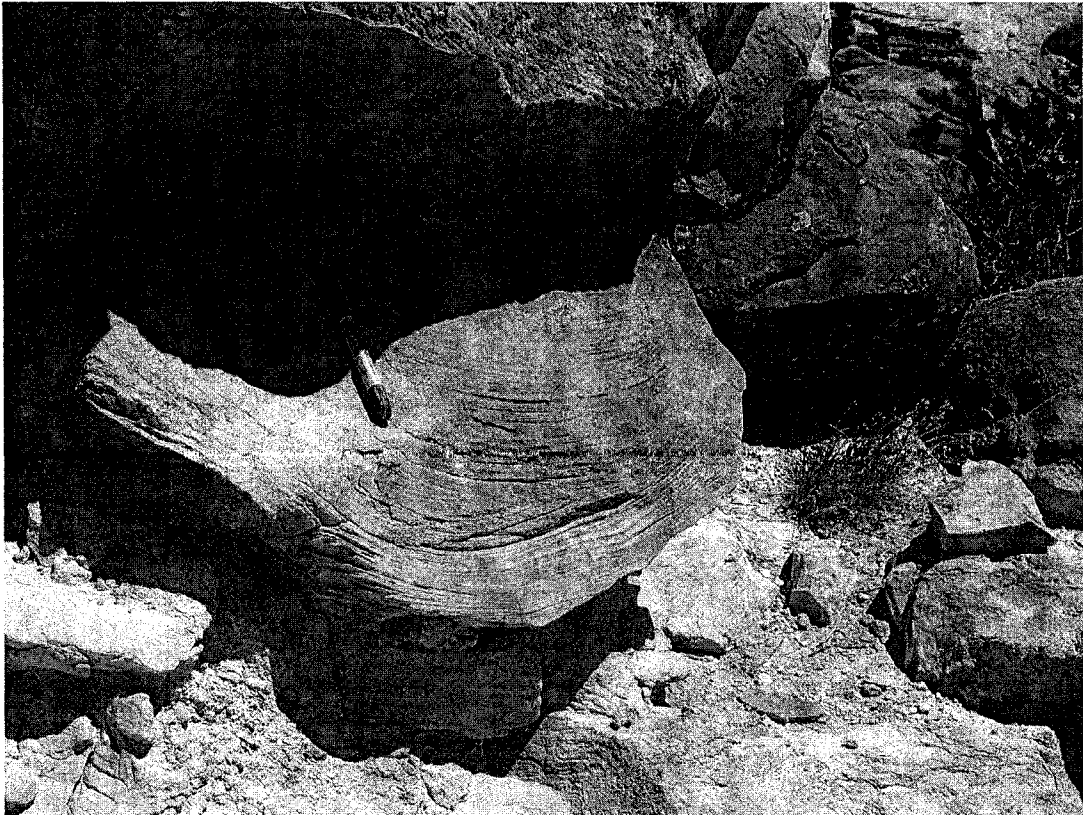


Figure 29.—Little Sand Draw gutter cast. Gutter cast seen in cross-section view in the V3 tongue of the Virgelle member.

bounded by regressive unconformities cut by sea level fall.

However, in this study, very few Virgelle beds showed evidence of sharp-based shorefaces. Of the eight Virgelle tongues observed, one (V2 at Wagonhound Bench, most up-dip transect made) showed some signs of sharp-based shorefacing, and seven exhibited gradational-based shorefacing (Fig. 26). In the seven examples, thin sandstone beds at the base are overlain by progressively thicker beds of the main sandstone tongue (Fig. 27). We may have been looking too far basinward to find sharp-based shorefaces. These seven gradationally-based sections appear to be in the lowstand turnaround tip of the tongues, seaward of the regressive ravinement (Fig. 27; Compare with Fig. 10a).

A few gutter casts were noticed within the Virgelle beds giving reason to believe that the regressive erosional surface was preserved in several tongues. The scarceness of the gutter casts may be due to the fact that in order to examine the casts, an exposed basal surface of the erosional bed is needed and not many such surfaces were found. Furthermore, the only evidence that we did find of gutter casts were examples observed in cross-section only, and hence cannot be clearly distinguished from load casts (Fig. 28 and 29).

The Gebo member was also examined for evidence of sharp-based shorefaces. The "G1" tongue has a noticeable erosional break between the underlying regressive muds and the overlying sandstone beds, although the overlying sands found in the Gebo may be channel sands rather than shoreface sands. The presence of the sharp-based Gebo bed could possibly show a transition period between the Virgelle and the Gebo's

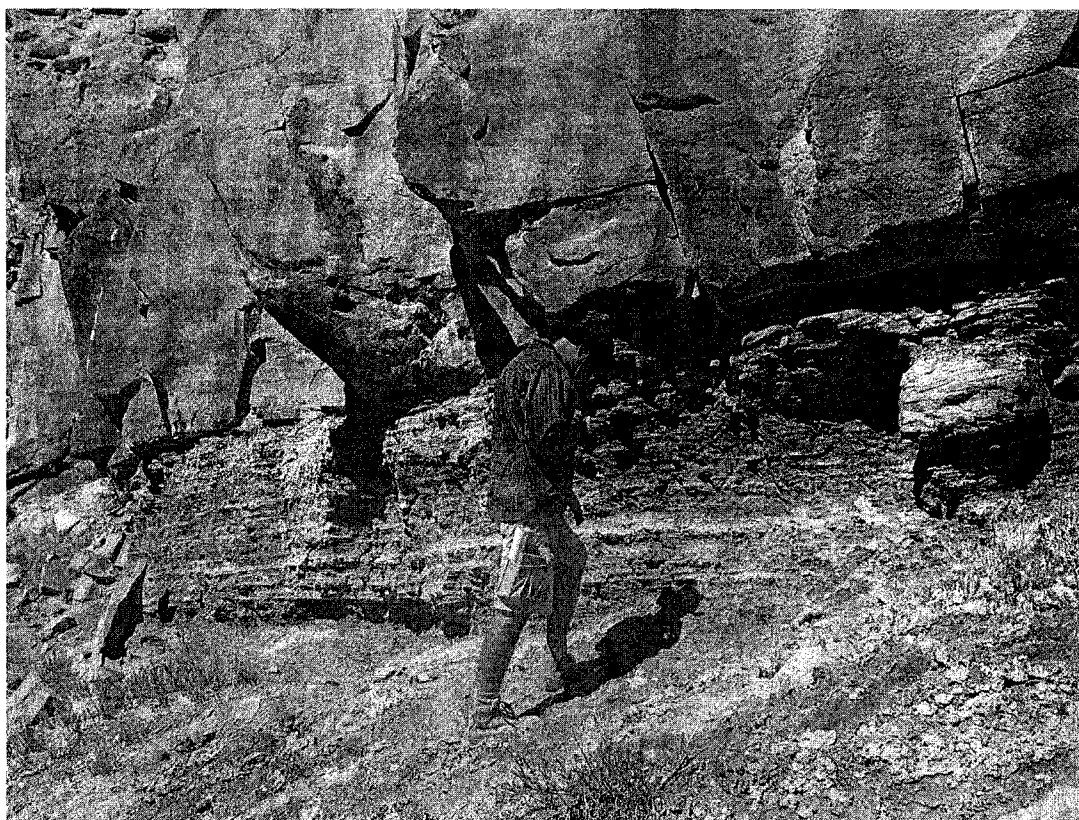


Figure 30.— West Cowboy Mine. G1 exhibits a sharp-based shoreface overlying regressive muds at the major unconformity.

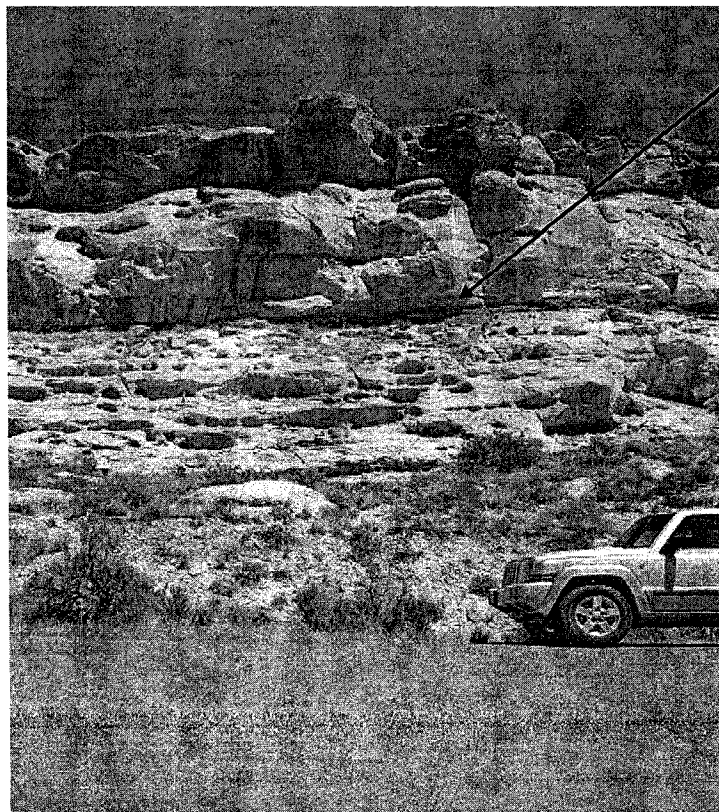


Figure 31.— Cowboy Mine. G2 overlying G1 coals. G2 shows evidence of sharp-based shorefacing.

a)



b)



*Thin coal above G1 and
below G2*

Figure 32.— Sharp-based and white clay. a) Ronoco Mine, the base of G2 is sharp-based and overlies a white underclay b) Cowboy Mine, a thin coal layer separating sharp-based G2 from G1

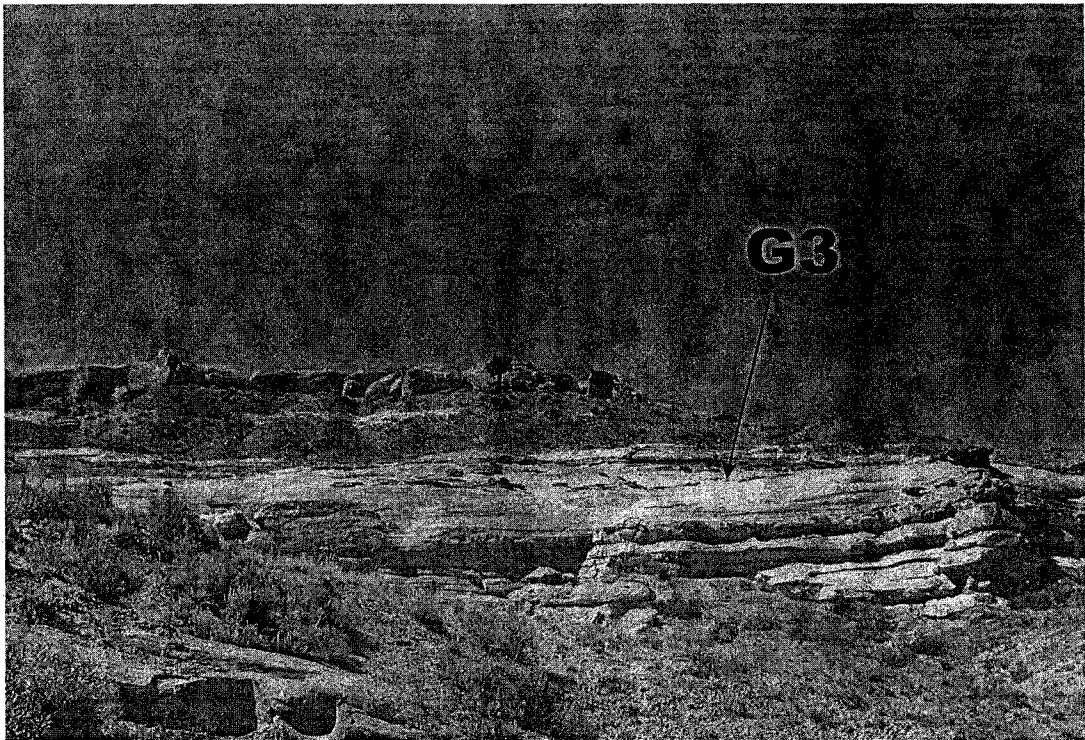


Figure 33.— G3 tongue of the Gebo at west Cowboy Mine, a gradational sandstone shoreface.

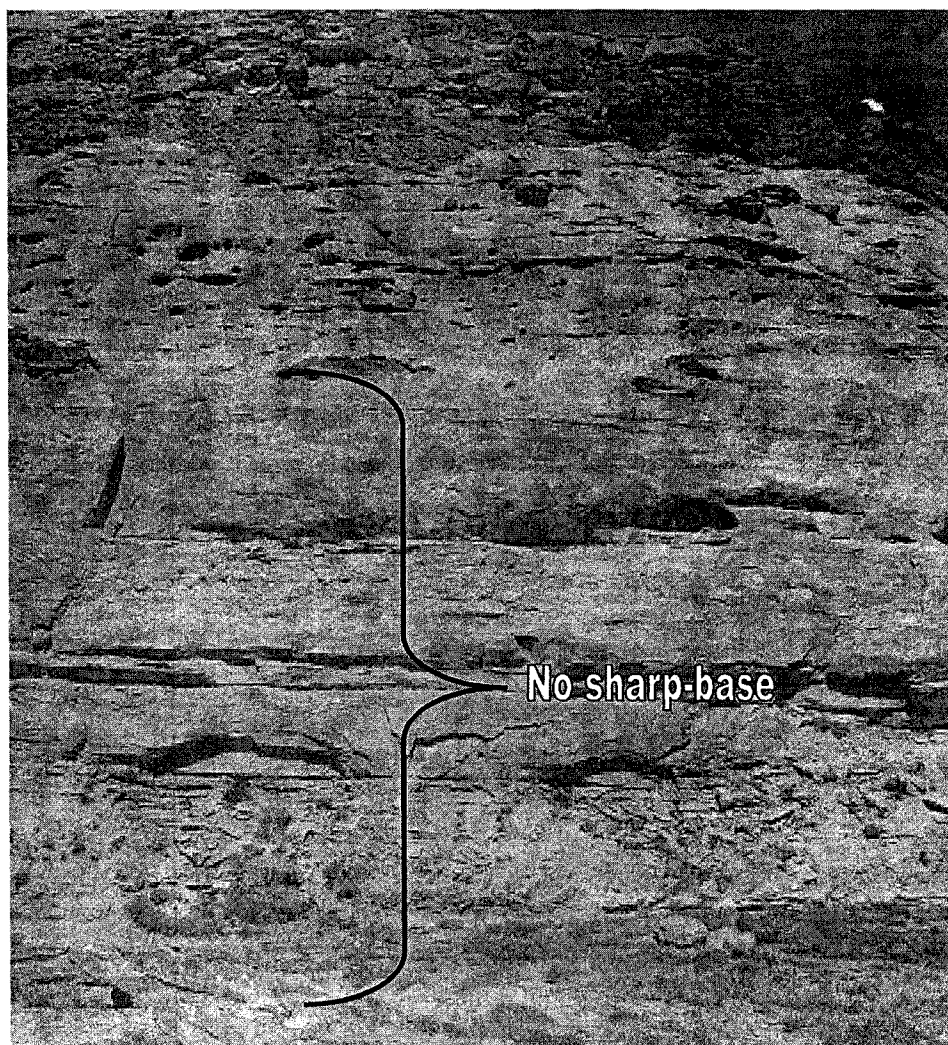


Figure 34.— The upper G3 sandstone at Syncline, revealing gradational base.

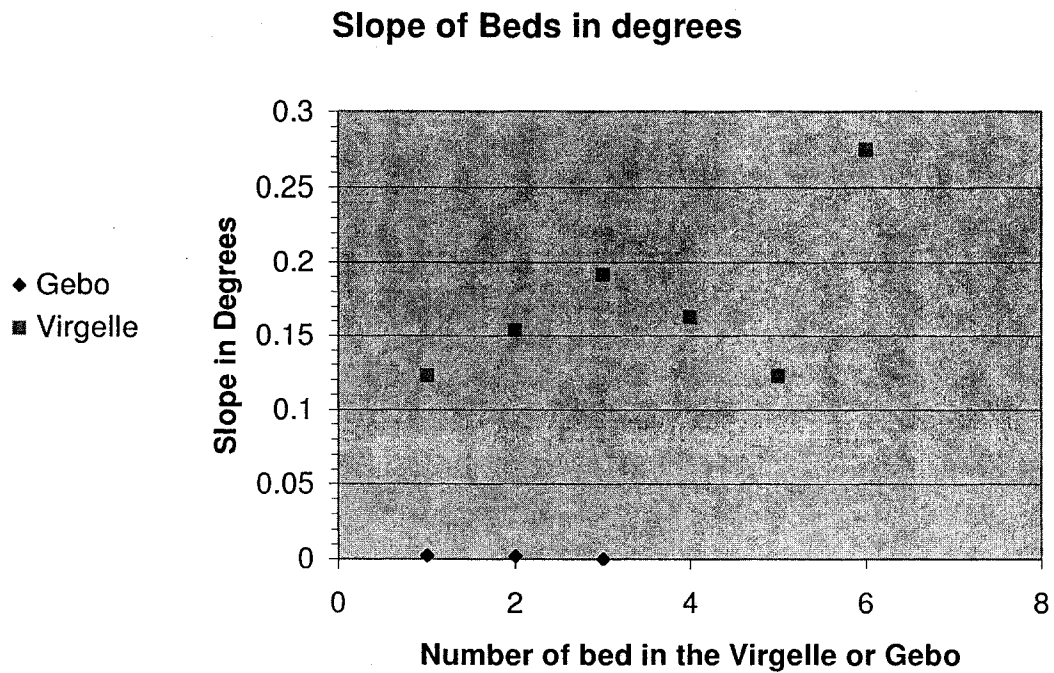


Figure 35.— Comparison of gradients of Virgelle and Gebo tongues measured from Klug's (1993) stratigraphic model.

depositional environments (Fig. 30 and 31). More probably, however, we are looking at the low-order erosional surface separating the Gebo Member from the Virgelle Member. At Ronoco Mine, and again at Cowboy Mine, the G2 tongue appears to be sharp-based and overlies a white clay and coal (Fig. 32). However, Klug (1993, Fig. 6a) argues that that G2 is here as a mouth bar deposit, not a shoreface deposit. G3 higher in the section, has clear gradational bases (Figs. 33 and 34).

The Virgelle did not exhibit sharp-based shorefaces or good examples of gutter casts as predicted. This may be explained due to the fact that other examples of distal portions of high frequency tongues show evidence of gradational-bases (Mellere and Steel 2000) and poor exposure of the erosional bed of the tongues existed along the transects. The Gebo shows moderate signs of sharp-based shorefacing and gradational shorefacing, depending on the tongue and location.

Gradients of high frequency tongues

It was predicted that the Virgelle tongues were deposited during a forced regression, and should be significantly steeper (an order of magnitude) than the overlying Gebo tongues. The Virgelle tongues were found to be significantly steeper than the Gebo tongues (Fig. 35). Measurements taken from Klug's model show the gradients of both the Virgelle and the Gebo tongues were low, however, the difference between the two was substantial. The Virgelle slopes more or less ranges from 0.1-0.3 degrees where the Gebo's slopes are a good deal less than 0.05 degrees. This result is consistent with the supposition that if the Virgelle was deposited under a forced regression so that the gradient of the Virgelle shoreface would be preserved. Furthermore, the Gebo beds show

little dip, perhaps due to its' deltaic architecture and free regression setting, dominated by a large sediment influx.

Sequence stacking patterns

Stacking patterns, a related parameter, were observed in the field and through previously published work. The hypothesis derived in this thesis predicts that the Virgelle was deposited during an oscillatory sea level fall, forming a progradational stacking pattern. However, the Gebo was deposited during a variable-rate sea level rise coupled with an increase of sedimentary input creating an aggradational stacking pattern.

As one walks east, into the basin, the basal tongues of the Virgelle begin to thin out and terminate. The younger, thicker-looking beds in tongues higher in the section extend further basinward, each moving the proximal facies (upper shore facies) further east than the bed below it (Fig. 23). The Virgelle thus shows good evidence of having a progradational (offlapping) stacking pattern. However, the Gebo demonstrates, thick, multi-story stacking that neither progrades into or retrogrades out of the basin. Each successive sequence is stacked directly on top of each other displaying an aggradational sequence (Fig. 34). Klug (1993) illustrates these two members' stacking pattern extremely well (Fig. 6a). The Virgelle is shown to have thin prograding beds that progressively shift basinward, reinforcing the prediction that the accommodation in the basin was much greater than the sediment input during the deposition of the Virgelle. An aggradational pattern is displayed through the Gebo sequences, characterized by stacks of beds from the same depositional environment on top of each other. At this time, the

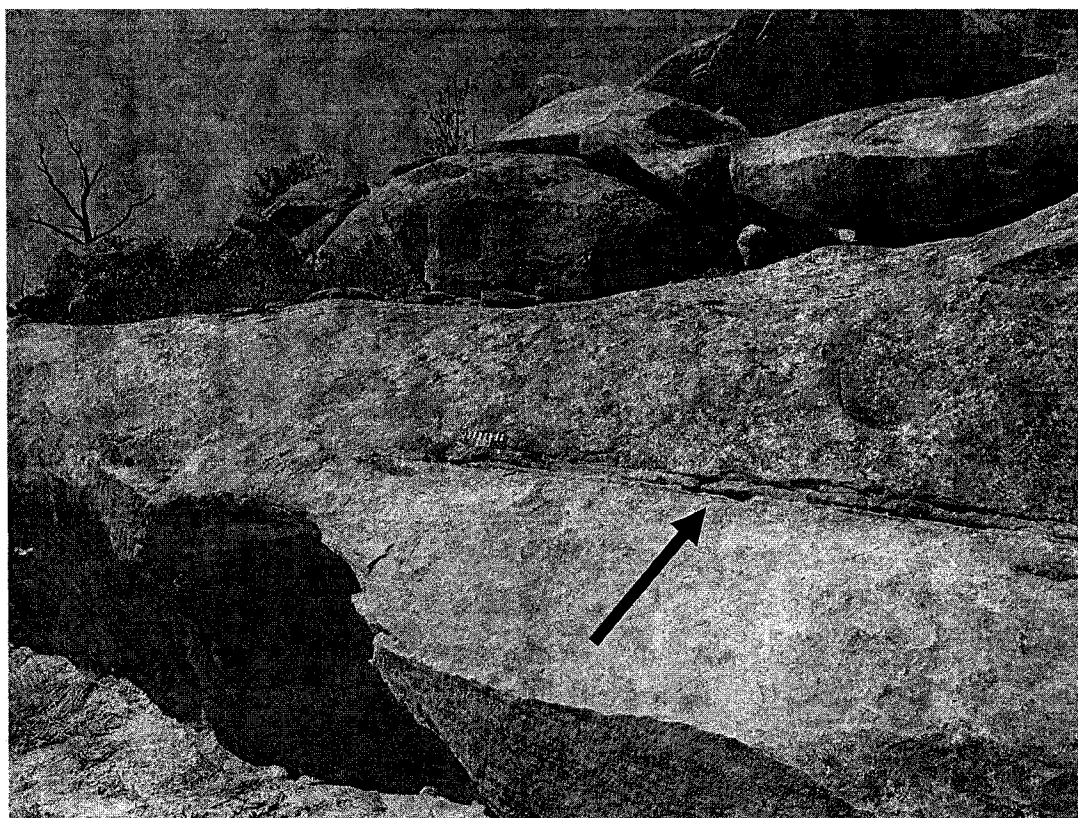


Figure 36.— Shale partitioning at Wagonhound bench. Within bed 2 of V2, a shale partition can be discerned at Wagonhound Bench but no indications of valley incision.



Figure 37.— Rip-up mud clasts within the V2 tongue at Wagonhound bench.

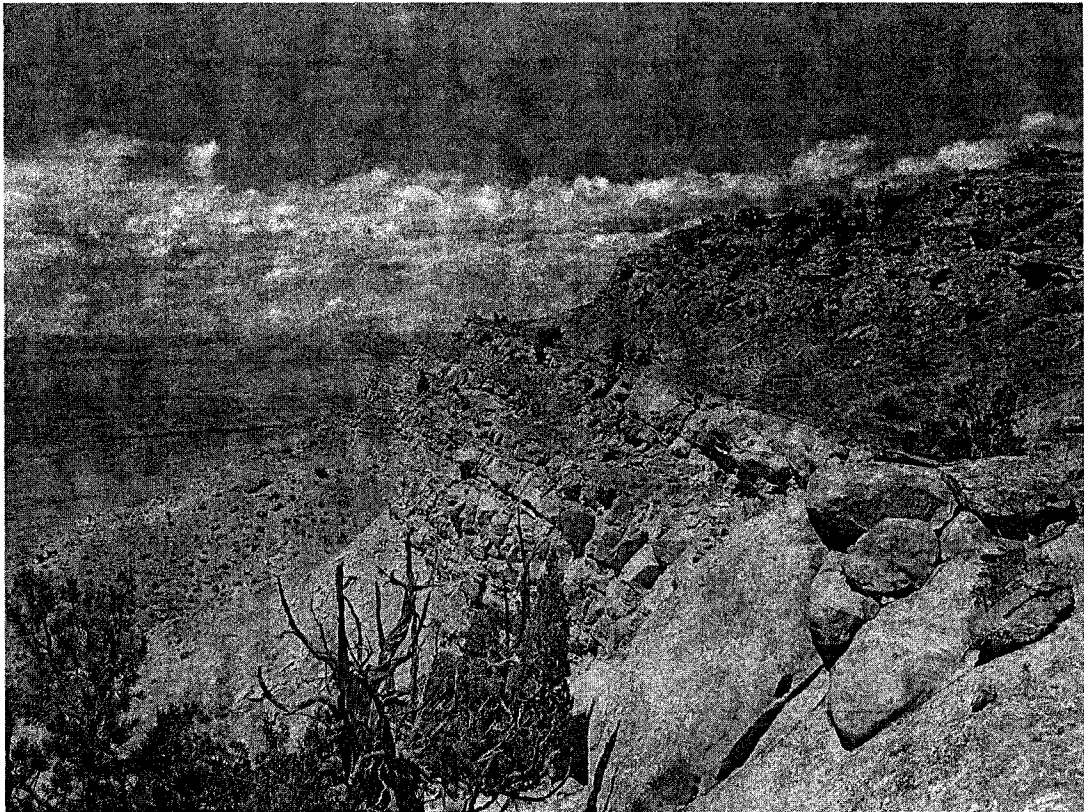


Figure 38.— Multiple event beds within the Virgelle tongues give it a multistory appearance.

sediment input was matching the creation of basin accommodation space, creating the thick aggradational sequence.

Incised valleys in high frequency tongues

My hypothesis predicts that while valley fills are to be expected in the Virgelle, they should be absent in the Gebo. In this study, it was found that the Virgelle tongues showed some “partitioning” and mud rip-ups but showed no signs of valley incision (Fig. 36 and 37). Bed partitioning develops from a short depositional change or hiatus within the bed, spanning laterally over a short distance, often with shale deposits, thus giving the bed a multi-story appearance. Such partitioning shales could occur in valley fills but are as liable to occur in or near distributaries. The incision of a valley wall should appear as a nearly horizontal contact that slowly rises from the bottom of the unit to the top as one walks from the center of the valley fill to its margin, parallel to the exposure. Ideally, the estuarine “sandwich” of fluvial deposits and bayhead delta (basal), central estuary mud deposit (middle), and capping estuary mouth bar sand, should be apparent (Dalrymple 1992). Depositional characteristics such as stacked channels with bi-directional trough cross bedding, fining upward, current ripples, wave ripples, and planar flat lamination should also be evident, though none was. The V4 tongue’s multi-story appearance of meter-scale repetitious storm beds (Fig. 38) could be linked to the 5th order Milankovitch cycles. It may be a high-quality example of a 41 thousand year obliquity cycle consisting of two 20 thousand year precessional cycles, but will require further work (Klug 1993).

The tongues of the Gebo were examined with particular care for indications of valley incision, since valley incision in the up-dip Gebo forms the core of Fitzsimmons and Johnson's (2000) model for the evolution of the Gebo. In particular, I walked out the tongues between Ronoco Mine and Syncline and between Gloin reservoir and Sand Draw, where valley walls appear in the detailed cross section of Fitzsimmons and Johnson (2000) (Figure 6b). No such breaks that could be interpreted as valley walls were observed.

Despite minor partitioning within the Virgelle, evidence of valley incision in the Virgelle and Gebo was absent. Even though the results do not fulfill my prediction of valley incision in the Virgelle, absence of evidence does not mean there is evidence of absence.

Major unconformity

I predict that the oscillatory sea level fall that deposited the Virgelle member was followed by a pulsed sea level rise that deposited the Gebo. Therefore, during the transition from Virgelle to Gebo, a low-order lowstand would have occurred, during which, the up-dip Virgelle would have undergone extensive erosion. Consequently, the contact between them should be a disconformity. In fact, both Klug (1993) and Fitzsimmons and Johnson (2000) report an unconformity between the Virgelle and Gebo members (Fig. 6a and 6b). Klug (1993) reports a local unconformity from Sand Draw to Lucerne (Fig. 8), but Fitzsimmons and Johnson (2000) believe that the unconformity marking a low order lowstand extends throughout the southern Bighorn Basin.

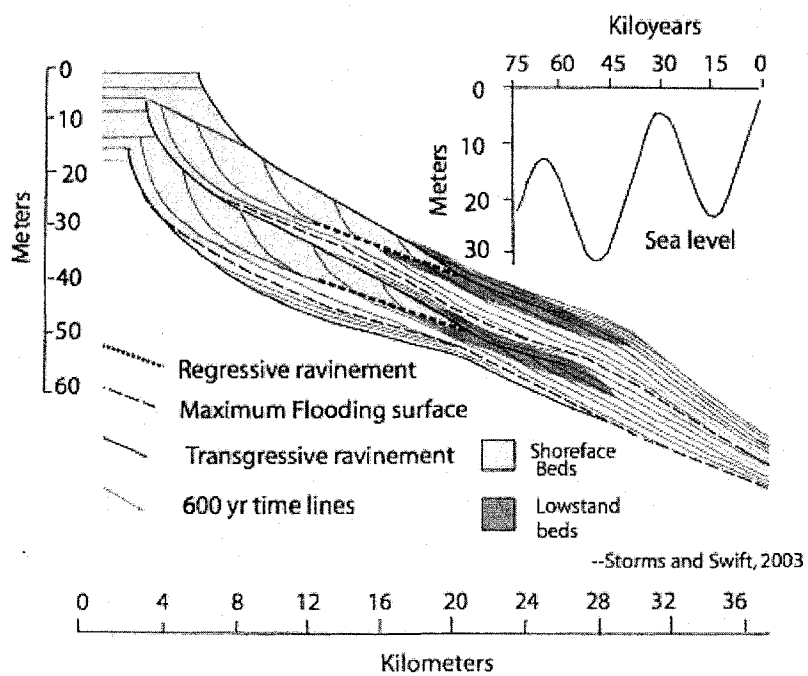


Figure 39.— Shoreface beds and lowstand beds prograding basinward within the numerical model. (from Storms and Swift 2003)

Disconformities, by their nature, are difficult to detect. This fact proved true for the sections studied here. As each prograding tongue was deposited, the leading edge of the low-order subaerial surface of erosion advanced basinward over it (Fig. 39). However, there is indirect evidence supporting the existence of a significant unconformity, as reported by Fitzsimmons and Johnson (2000), and Klug (1993). The terrestrial section of the Virgelle, equivalent to the up-dip portion of the Gebo, with its terrestrial shales, shoestring sands, and crevasse splays is gone. In the Virgelle, all of the shale between the sandstone tongues is marine; terrestrial shale like those of the Gebo member is absent. Progressive subaerial exposure during a sea level fall appears to have “beheaded” the up-dip Virgelle supporting the prediction of a low-order lowstand of sea level between the Virgelle and the Gebo.

DISCUSSION AND CONCLUSIONS

The preceding observations show that the Virgelle and the Gebo members record very different depositional and sea level characteristics. The Virgelle and the Gebo tongues show distinctively different thicknesses in the field. When computing the measured sections from Klug (1993), Virgelle tongues are thin, typically a few meters thick, whereas Gebo tongues are blocky sequences tens of meters thick. The Gebo tongues have significantly flatter gradients than do the Virgelle tongues. The evidence presented in this thesis supports the contention of Fitzsimmons and Johnson (2000) that the Virgelle is the production of an oscillatory sea level fall and the Gebo are separated by an unconformity of interregional extent. However, it was not possible to reproduce the

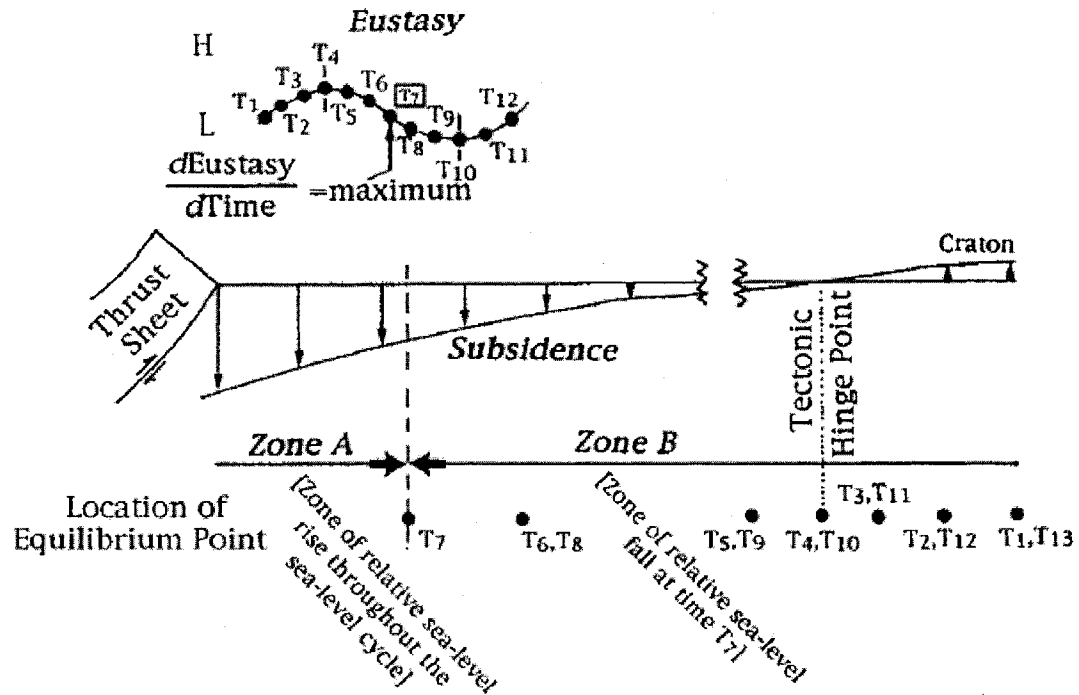


Figure 40.— An illustration showing foreland basin rates of subsidence. Zone A is defined as the region within which the rate of subsidence always exceeds the rate of sea level fall. Zone B is defined as the region within which the rate of eustatic fall periodically exceeds the rate of subsidence. The Bighorn Basin shifted between these two zones during the Virgelle and Gebo deposition. (Posamentier and Allen 1993)

Fitzsimmons and Johnson (2000) observations with respect to valley incision during falling stage. In particular, the examples of valley incision cited by these authors in the Gebo Member could not be found. Observations described above suggest that on the contrary, the Gebo was deposited during a period of enhanced sediment input and continuous, rate-varying sea level rise.

In the broader context of Campanian sedimentation, the Bighorn Basin underwent a series of mountain building events, creating a foreland basin that was flooded by seawater during the late Mesozoic Era. Throughout the mountain building event, the early middle Cretaceous foredeep was widening into a much broader zone of rapid dynamic subsidence (DeCelles 2004). At the same time, thick-skinned tectonics between the Farallon plate and North American plate led to the Laramide deformation and creation of separate smaller basins (DeCelles 2004). Van Wagoner (1990) was the first to introduce the concept of the loss of high order sea level falls through tectonic rectification, although he did not use that term (See Fig. 1, this thesis). Posamentier and Allen (1993) expanded on the subject, distinguishing two tectonostratigraphic zones, zone A and B (Fig. 40). They suggest that proximity to the orogenic belt governs the amount of tectonic influence on the developing stratigraphy. Subsidence at the foredeep is substantial and may be rapid enough to constantly outpace sea level changes, zone A, whereas further distal locations would only periodically exceed the rate of eustatic change, zone B (Posamentier and Allen 1993). Building on Posamentier and Allen's previous work, Yoshida et al. (1996) postulate that the zones set by Posamentier and Allen (1993) can migrate landward or seaward in response to changes in long-term basin subsidence. With

increased subsidence, the area of tectonic influence will expand, decreasing the area of periodic rectification and vice versa.

In the case of the Bighorn Basin and the Eagle Formation, the evidence shows that the evolution of the Virgelle and the Gebo Members were coupled closely to eustatic and tectonic changes. At the time of the Virgelle deposition, the subsidence rate was too low to reverse eustatic sea level fall. During Gebo deposition, the changing geodynamics expanded the zone of rapid subsidence and at the same time generated uplifts that shed sediment. Tectonics became more active and the foredeep widened, shifting the tectonostratigraphic zones basinward. The Bighorn Basin appears to be characteristic of the proximal portion of Posamentier and Allen's (1993) zone B, where eustatic fall only periodically exceeds subsidence.

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 - Proposed possible solutions to the violations of the engineering and erosion control requirements set by the state of Virginia
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